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LIMONITE TYPES DERIVED FROM BORNITE AND TETRAHEDRITE.

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BECAUSE of its rarer occurrence, bornite is less important as a copper ore than are chalcopyrite and chalcocite. Its oxidation products as a consequence have received less consideration in the Leached Outcrops Investigation. But in the writers' experience the commercial feasibility of testing a prospect has hinged, in at least one instance, upon whether the leached outcrop represented a 50–50 mixture of bornite and chalcopyrite, or chalcopyrite only. And bornite is encountered in field work fre-

quently enough to make familiarity with its leached products desirable.

Tetrahedrite, though even less important as a copper ore, so frequently carries high silver values in lead-silver deposits, and in other sulphide mixtures, that its identification in leached outcrops likewise has commercial significance.

For these reasons the identified limonite types characteristic of bornite and tetrahedrite are described.

Technical terms are used in the same sense as in previously published papers, with which the reader is presumed to be familiar.[1]

Products described are indigenous.

DESCRIPTIONS OF LIMONITE TYPES.

Bornite.

Five limonite types have been differentiated which characterize bornite. Of these, triangular boxwork is the identifying, or "key," structure, usually present to a greater or less extent in each of the other types.

Triangular Boxwork.—Triangular boxwork consists of a cell, or composite of cells, that in shape roughly resembles a spherical triangle. Rarely the shape may be trapezoidal, and in some instances one or more sides are rounded sufficiently to produce an eye-shaped, elliptical, or more rarely a cup-shaped structure. But

[1] Charles Henry White: "Prospecting for Disseminated Copper by a Study of Leached Croppings." *Eng. & Min. Jour.*, March 22, 1924.

H. W. Morse and Augustus Locke: "Recent Progress With Leached Ore Capping." ECON. GEOL., vol. 19, no. 3, April–May, 1924.

Roland Blanchard and P. F. Boswell: "Notes on the Oxidation Products Derived from Chalcopyrite." ECON. GEOL., vol. 20, no. 7, November, 1925.

Augustus Locke: "Leached Outcrops as Guides to Copper Ore." Williams & Wilkins, Baltimore, Md., 1926.

P. F. Boswell and Roland Blanchard: "Oxidation Products Derived From Sphalerite and Galena." ECON. GEOL., vol. 22, no. 5, August, 1927.

Roland Blanchard, and P. F. Boswell: "Status of Leached Outcrops Investigation." *Eng. & Min. Jour.*, Feb. 18 and March 3, 1928.

P. F. Boswell and Roland Blanchard: "Cellular Structure in Limonite." ECON. GEOL., vol. 24, no. 8, December, 1929.

these are infrequent variations; the predominating structure is triangular, with usually one or more edges curved enough to suggest a spherical triangle.

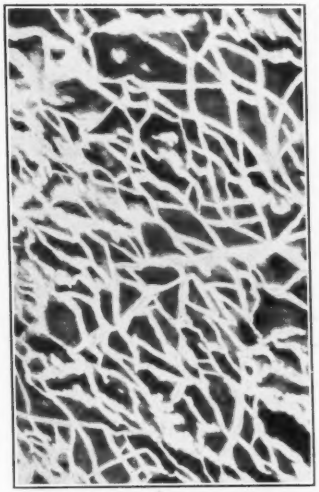

FIG. 1. Triangular boxwork derived from bornite. Note frequent occurrence of the spherical triangular pattern. This is the "key" structure, usually present to a greater or less extent in all limonite of bornite derivation. Ruby Mine, Plumas County, California. ×5.

Although this structure is common to small cells, it stands out most prominently when extending in a straight or slightly curved line past numerous cells. In such case it may become the container or enclosure within whose limits from two to a dozen or more of the smaller cells lie. Individual cells of triangular boxwork vary in longest dimension from 1 to 10 mm. Their walls ordinarily range in thickness from 0.05 to 0.5 mm.—approximately twice the thickness of corresponding structures of chalcopyrite derivation.

The larger and more definitely formed triangular boxwork

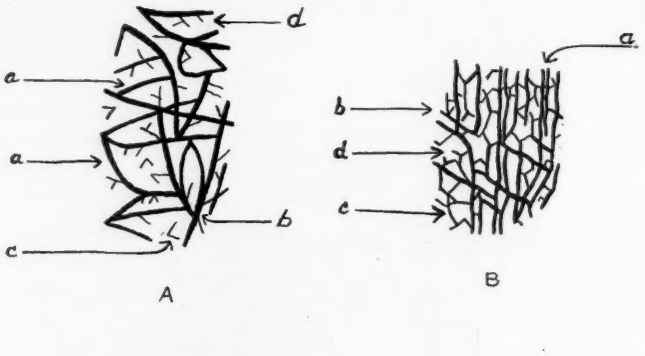

FIG. 2. *A.* Sketch emphasizing characteristic curved "spherical" triangular cell pattern of limonite boxwork derived from bornite. Extreme type. Engelmine, California. × 5. *a*, conspicuous spherical triangular and trapezoidal cell pattern; *b*, occasional rounded or eye-shaped cell pattern; *c*, isolated limonite webwork fragment marooned within larger cell, usually reproducing triangular pattern; *d*, incomplete webwork within larger cell.

B. Sketch emphasizing characteristic parallel, quadrangular cell pattern of limonite boxwork derived from chalcopyrite. Extreme type. Duquesne, Arizona. × 5. *a*, conspicuous parallelism of cell walls; *b*, generally prominent parallel cross structure; *c*, thin-walled, sharply angular webwork between larger parallel cell walls, rarely suggestive of triangular pattern; *d*, incomplete webwork within larger cell.

C. Sketch showing characteristic cell pattern of limonite derived from bornite. Average type. Lookout prospect, Black Mountains, New Mexico. × 5.

D. Sketch showing characteristic cell pattern of limonite derived from chalcopyrite. Average type. Creston Verde property, near Choix, Sinaloa, Mexico. × 5.

structures often are filled with a discontinuous, fine cellular webwork that reproduces to some extent the triangular or trapezoidal pattern of the larger boxwork structure.[2] (Fig. 2, *A*.) But usually the webwork is so fragile that a light jar in handling the specimen disintegrates it, and leaves only the coarser structure shown in Fig. 1.

The curved, "spherical" triangular boxwork pattern has thus far been found peculiar to limonite of bornite derivation, and has not failed as a dependable guide for identifying leached bornite outcrops in the field. Because bornite and chalcopyrite are so often associated in nature, the feature is especially serviceable on account of its contrast with the more definitely parallel, and more or less quadrangular, cell pattern in limonite derived from chalcopyrite.

In the sketches of Fig. 2 the limonite crusts, flakes, rosettes, grains, and pulverulent particles that ordinarily coat cell walls and often largely fill individual cells, are not shown. It is obvious that with cell walls coated or crusted with these limonite flakes and grains, basic cell pattern would be partly obscured; and contrasts, especially in cases such as *C* and *D*, would stand out less vividly than in the sketches. But beneath the camouflage of cell wall coatings the basic or "key" structure in each case is generally distinguishable where carefully searched for, and serves to differentiate cellular boxworks derived from the respective sulphides.

Limonite Sponge.—Limonite sponge differs from boxwork in that its cells are irregularly but characteristically rounded rather than sharply angular.

The sponge is yielded by chalcopyrite, bornite, sphalerite, galena, pyrite, pyrrhotite, and various other minerals. In the case of bornite the cells are rarely fully rounded; the spherical triangular pattern is more or less preserved, and the product grades insensibly into triangular boxwork.

In all limonite sponges thus far studied except those derived

[2] To avoid confusion the larger, more definitely formed cellular structures are called boxwork. The more fragile, broken cellular structures contained within the boxwork are called webwork.

from bornite and pyrite, the sponge has a generally uniform cell size. This does not mean cell diameters maintain consistent regularity, like oranges in a box; it means disparity in cell size is

FIG. 3. Limonite sponge derived from bornite. Note the insensible gradation into triangular boxwork, with frequent outstanding spherical triangle structures, often suggesting a "wishbone." Note also frequent disparity in cell size, relatively thin cell wall as compared to cell diameter, and frequent incomplete webwork. LaSalle Mountains, Utah. Natural size. Compare with Fig. 1.

not striking enough in the hand specimen to attract special attention. In the case of bornite and pyrite such disparity is marked; often a cell may be 20 to 30 times as large as those immediately adjoining; and this condition is not rare, but common.[3]

[3] In ordinary limonite "boxwork," as contrasted with sponge, disparity in cell size is so common, regardless of the limonite's origin, as to have little or no significance.

The following features serve to distinguish bornite and pyrite limonite sponges from each other:

1. The bornite product usually contains incomplete webwork, or broken, fragile cell structure; the pyrite product usually is firmly knit, without markedly thin or incomplete cell structure of any sort.

2. In the bornite product a cross section commonly shows diameter exceeding cell wall thickness from 5 to 25 times. In the pyrite product cross section commonly shows diameter not greatly exceeding, and often exceeded by, cell wall thickness.

3. In the bornite product the spherical triangular, trapezoidal, or elliptical cell structures always show up to some extent, increasing as the specimen grades into triangular boxwork. In the pyrite product cells almost as consistently show an irregularly round to oval structure, and the entire mass is more or less coated with the smeary crusts and finely nodular films which characterize limonite of pyrite derivation.

Cellular sponge derived from bornite is not always easy to identify with certainty; but the features above discussed, together with the partially sintered and the caked limonite crusts described below—which often coat cell walls and partly fill cell cavities—usually serve, in connection with the sponge characteristics above described, to establish the product's origin.

Partially Sintered Limonite Crusts.—Partially sintered limonite crusts have been described in a previous paper as an oxidation product of galena and cerussite.[4] This type of limonite is so called because under the hand lens the aggregates of limonite particles have a partially sintered appearance, like the surface of dead-burned magnesite brick but slightly rougher.

Next to the triangular boxwork and limonite sponge the partially sintered crusts are the most common limonite products of bornite. Often they occur as coatings on cell wall surfaces of the boxwork or sponge. From this they grade into compact aggregates within which cellular structure may be nearly or wholly obliterated.

The shape and other physical characteristics of these partially

[4] ECON. GEOL., vol. 22, no. 5, August, 1927, page 432.

sintered crusts are not readily portrayed by sketch, nor has the product been effectively photographed. Perhaps a crude idea of its appearance may be obtained if the reader imagines himself looking through an inverted field glass at the side of a swallow's nest, and assuming that the nest is made up of small aggregates or dabs of partially sintered limonite granules instead of small dabs of mud. The inverted field glass will give a reduction in size to the mud dabs of the nest comparable to the magnification of the limonite granules by a 12 × to 16 × lens; and relief in both cases will be about the same.

That of course represents the extreme type of partially sintered crusts. Usually more or less webwork, or fine cellular structure, emerges through the crusts, as projecting corners and edges of boxes protrude from a tailings pond in which the boxes are becoming submerged; and as these projecting cells generally reveal in some form the triangular boxwork or sponge patterns already described—just as the protruding cellular structure in the corresponding product of galena reveals the characteristic "cleavage" boxwork of that sulphide—determination of the origin of the partially sintered crusts in either case is ordinarily not difficult.

But to avoid confusion certain distinctions between the crusts derived from galena and bornite are emphasized:

1. With galena the crusts commonly occur only as coatings of cell walls, are loosely aggregated, rarely extend halfway across individual cells, and ordinarily occupy not more than 25 per cent. to 40 per cent. of the cell volume. With bornite the crusts often obliterate nearly the whole cellular structure, the granules are closely aggregated, one cluster encroaches upon another (like mud dabs in the swallow's nest), and the crusts ordinarily occupy from 50 per cent. to 90 per cent. of the cell volume.

2. The rigid parallelism, and the cube structure of the "cleavage" boxwork is rarely entirely absent in the product derived from galena; usually it is strongly defined. The triangular boxwork, likewise, is rarely wholly absent in the product derived

from bornite, though ordinarily it is much less conspicuous than is the "cleavage" boxwork in galena limonite.[5]

3. Partially sintered limonite crusts have not thus far been found so effectively masking cellular structure in galena limonites as they do in the bornite product. And the writers know of no other common iron-yielding mineral except specularite in which almost complete submergence of angular (as distinguished from rounded) cell structure occurs. Specularite does not yield the partially sintered limonite crusts. Where almost complete submergence of angular cell structure by partially sintered crusts is in evidence, the presumption therefore is strong that bornite, rather than galena, is the sulphide that has been leached.

In the field little difficulty is usually experienced in determining whether bornite or galena is involved. Neither bornite-galena nor bornite-specularite mixtures are common in nature. And in the actual outcrop and its surroundings other evidences besides the products here discussed ordinarily furnish a clue as to which mineral was the source of the limonite.

Caked Limonite Crusts.—Somewhat resembling partially sintered crusts are the caked limonite crusts. They are kaolinic masses thoroughly impregnated with limonite, usually containing numerous polygonal shrinkage cracks, with the intervening clayey masses curled up around their edges so as to resemble in miniature the surface of dried mud flats. The clayey masses are generally, though not always, orange-red to Indian-red in color. Ordinarily the product carries from 30 per cent. to 40 per cent. Fe.

Microscopic determination has shown these crusts in most cases to be the disintegrated oxidation end products of copper or limonite pitch. They differ from true pitch in possessing a slightly roughened instead of glazed surface, in being earthy, caked, and usually porous instead of submetallic or vitreous, and in possessing the fine, generally polygonal, shrinkage cracks above referred

[5] Locally, parallel orientation of cell walls has been observed in limonite boxwork derived from bornite. But the parallelism is neither rigid nor consistent in occurrence; it approaches more nearly the suggestion of parallel boxwork illustrated in Fig. 2, *C*. And it grades invariably in the course of a few cell lengths into the characteristic triangular boxwork. The structure therefore never need be confused with the "cleavage" boxwork of galena.

FIG. 4. Partially sintered limonite crusts derived from bornite. These are best developed in upper portion of picture where they almost completely obscure sponge and boxwork structure. Elsewhere they occur as local incrustations coating the triangular boxwork and sponge. Emergence of triangular boxwork in itself suggests bornite derivation, though in this case, without the partially sintered crusts, it would not prove derivation of the specimen exclusively from bornite. Las Palomas property, northern Tallace, Mexico. ×3.5.

to, with the intervening clayey masses curled up around the edges like the surface on dried mud flats. Usually, too, remnants of fine cell structure project faintly through or around the caked masses.

Caked limonite crusts are derived from malachite, azurite, chrysocolla, bornite, pyrite, pyrrhotite, magnetite, and various other minerals. By themselves they are not significant unless they possess distinguishing features which differentiate them from crusts of other origin.

In the case of bornite, they possess such distinguishing features. Instead of being essentially structureless, limonite-soaked "iron-clay" masses that occupy the entire space of the former sulphide nodule or other mineral, they (1) have been found only as fillings of individual cells or of the larger triangular cellular structures; (2) they are nearly always composed of individual superposed layers of clayey limonite from 0.05 to 0.3 mm. thick; (3) the edges of individual small crust polygons are curled up much more than in ordinary caked structures of this sort, which gives their exposed surfaces a semi-flaky appearance; (4) within the crusts themselves are often visible isolated small remnants of the characteristic triangular boxwork.

In the field, caked limonite crusts usually occur only under conditions where surface impurities, such as fine clay, were being introduced by ground waters during oxidation. In volume the crusts probably never constitute more than 35 per cent. of the total leached material derived from a given bornite mass, and probably never represent more than 20 per cent. of the former copper content. Usually they represent much less. But a knowledge of their origin, and their meaning in terms of the original bornite, is desirable in cases where quantitative estimates are attempted of the copper formerly present in an outcrop.

Relief Limonite.—In previous papers relief limonite has been definited as a product pulverulent in appearance, but showing above or through the pulverulent mass minute projections of limonite rosettes, or of an indefinite fine cellular structure, that under the hand lens stand out in prominent relief like objects in a stereoscopic slide.

FIG. 4. Partially sintered limonite crusts derived from bornite. These are best developed in upper portion of picture where they almost completely obscure sponge and boxwork structure. Elsewhere they occur as local incrustations coating the triangular boxwork and sponge. Emergence of triangular boxwork in itself suggests bornite derivation, though in this case, without the partially sintered crusts, it would not prove derivation of the specimen exclusively from bornite. Las Palomas property, northern Jalisco, Mexico. ×3.5.

Relief limonite is a common product of bornite oxidation in all gangues. It is especially prominent in kaolinized ones, such as the acid-attacked feldspar gangues, and in those of strong neutralizers, such as limestone. In quartz gangues it develops less conspicuously, but is frequently present.[6]

Relief limonite is not peculiar to bornite; it has been found in the field derived from chalcocite, covellite, bornite, galena, and other minerals. When of bornite derivation it generally shows more pronounced relief than when of other origin. The minute projections stand out from the pulverulent matrix even without the hand lens, and impart to the product in the hand specimen a soft, velvety texture much more vivid than in relief limonites of other derivation. Furthermore, under a hand lens of 16 × to 20 × magnification the triangular boxwork, or "key" structure, of bornite usually may be to some extent distinguished. But the striking feature under the hand lens is not the cellular structure itself but the fact that the apparently pulverulent matrix is in large part composed, not of fluffy limonite particles or limonite rosettes as would naturally be supposed from its velvety texture, but of extremely fine aggregates, arranged in "hit and miss" pattern, of the partially sintered crusts above discussed. The abundance of these in the matrix in minute form and in heterogeneous arrangement accounts for the greater relief and the softer and more velvety texture which in the hand specimen differentiate this product from relief limonite of other origin.

The "velvety" relief limonite is nearly always conspicuous in leached outcrops derived from bornite, regardless of other limonite types present. Usually, though not always, it possesses a striking ochreous-orange color on fresh surfaces. The observer acquainted with these peculiarities is not likely to pass it by unnoticed, or to confuse it with relief limonite of other derivation.

Summary.—Of the five limonite types described, only the "spherical" triangular boxwork is peculiar to bornite; the sponge, partially sintered crusts, caked limonite crusts, and relief

[6] Where relief limonite occurs in quartz gangues the presence of extraneous neutralizer is suggested; but such limonite may conceivably form through dilution or hydrolysis.

limonite are types commonly derived from other minerals. Although each of the four last named, when of bornite derivation, possesses its distinguishing physical characteristics which the experienced observer will recognize and which serve to establish its origin, the identification of any of them may be more convincingly verified through recognition of the triangular boxwork structure which to a greater or less extent emerges from or through each of them. The "velvety" relief limonite, where present, also aids in identification of the limonite product.

Tetrahedrite.

Pure tetrahedrite has the composition $4Cu_2S.Sb_2S_3$. But the ordinary tetrahedrite of nature has a much more variable composition. Frequently it carries from a few ounces to 30 per cent. silver, the variety high in silver being called freibergite. Frequently, too, a greater or less amount of arsenic is present, the antimony and arsenic being completely isomorphous.

Most of the tetrahedrite studied in the field and laboratory in this investigation carries silver. It has not been observed that either high or low silver content affects the type or pattern of limonite produced. Arsenic also is present in most of the material, but only in small amount. The arsenic, likewise, has not been observed to affect the type or pattern of limonite produced, though, as discussed below, staining by oxidized arsenic compounds may occur.

The term tetrahedrite, as here used, therefore inclues both the silver and non-silver bearing mineral, with or without small admixture of arsenic. The writers have not seen pure tennanite ($4Cu_2S.As_2S_3$) oxidizing in the field, and have no opinion as to whether or not its oxidation products resemble those of tetrahedrite.

Two limonite types of tetrahedrite origin have been identified. Various gradations and modifications of both occur, but the basic structure for each type remains constant.

Contour Boxwork.—Tetrahedrite yields the most distinctive boxwork pattern yet encountered in the Leached Outcrops In-

vestigation. The cells are long, narrow, and approximately twice as deep as corresponding cells of other limonite types. The longer cells curve abruptly, and individual walls of cells contain sharp angles. The boxwork, when viewed in cross section, bears close resemblance to the contour map of a steeply mountainous region. For that reason the name contour boxwork is applied to the product.

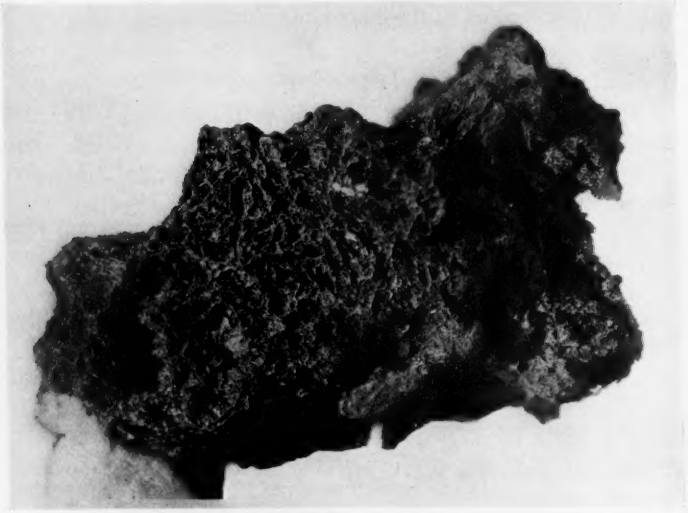

FIG. 5. Contour boxwork derived from tetrahedrite. Note suggestion in cellular pattern of the contour map of a steeply mountainous region. Right edge of specimen shows the coagulated type of limonite described later. Hachita, New Mexico. ×4.

Length of cells is 0.2 to 10 mm.; width from 0.05 to 1.5 mm. Length ordinarily exceeds width 2 to 10 times. Cell wall thickness varies from 0.03 to 0.25 mm. Despite the fact that cells often are abruptly angular, and the cells much deeper than usual, cell structure is remarkably rigid, due to the characteristically hard limonite and closely joined cell walls.

Firmly coating the cell walls is a thin, continuous mat of fine grained, sandy, dully resinous granules that glisten faintly in the sunlight, and somewhat resemble the roughened surface of sand paper, but with the granules more irregularly sized. In no case have there been found the curved rosettes, or the flaky limonite particles, common to most cellular boxworks of copper origin.

FIG. 6. Sketches emphasizing characteristic contour boxwork pattern of limonite derived from tetrahedrite. In the sketches have been omitted the sandy and dully resinous granules that coat cell walls and partly fill cell cavities. With cellular structure alone showing, resemblance to contour map of steeply mountainous country is striking. Compare with Fig. 5.

A. Gillespie property, Hachita, New Mexico. × 5.
B. World's Fair mine, Patagonia, Arizona. × 5.

Frequently contour boxwork carries crystalline and granular masses of colorless, pale yellow, or white scabs that, like barnacles, locally incrust the cellular mass. More often the scabs cling to the outcrop in cracks and depressions immediately adjacent to the boxwork. Often the material consists of a pulverulent to chalky yellow-white product, rather than of a granular or crystalline one.

Usually the chalky and crystalline products are so intergrown that specific minerals cannot be identified. But both the crystalline and chalky products, upon test, yield strong antimony reactions, and the incrustations clearly consist of one or more of the antimony oxides, usually with other oxide impurities such as alumina or silica. The presence of these yellow-white incrustations, in association with contour boxwork, points unmistakably to tetrahedrite.[7]

[7] A. S. Walter, who during the past year has conducted extensive laboratory tests of antimony oxides at the New Mexico School of Mines, states (private

FIG. 7. Contour boxwork derived from tetrahedrite. White incrustations of antimony oxides show plainly upon the limonite boxwork. Elkhorn, Montana. × 6.

The presence of minute, scattered granules of the antimony oxides, dimly embedded among the sandy limonite particles which

communication) that the various oxides such as valentinite, cervantite, and stibiconite almost invariably are intergrown with one another in antimony oxide precipitates of the Southwest; that definite and complete crystal forms are rarely developed; and that even where distinct crystal form points to such minerals as valentinite or senarmontite, tests generally show a 25 per cent. to 50 per cent. admixture of impurities such as silica and alumina. Where the oxides develop in limestone gangues a greater or less admixture of secondary lime products occurs. Despite the common absence of individual crystal form, and the general presence of such impurities as alumina, silica, and the lime products, no difficulty is ordinarily experienced in establishing the yellow-white incrustations as antimony oxides.

coat the cell walls of contour boxwork, accounts in large part for the dully resinous luster, and the faint glittering in the sunlight, of the latter product.

In rare instances leached outcrops derived from tetrahedrite carry the apple green stain (presumably ferrous arsenate) of oxidizing arsenic compounds; but this is not common, even where tests of the underlying sulphide ore show arsenic to be an important constituent.

Not infrequently contour boxwork contains isolated small crusts, globules, and specks of marooned hornsilver. They are most common in deposits of the arid region, as at the World's Fair mine in Arizona.

Less frequently ruby silver remains in small amounts, as at the Gillespie property near Hachita, New Mexico. This, however, occurs only where the mineral was protected from both erosion and chemical attack.

But even without the antimony, arsenic, or silver oxidation products as a guide, the contour boxwork is so characteristic and distinctive that no difficulty is experienced in its interpretation. Once clearly visualized, it is the least likely of all to be confused with other limonite types.

Coagulated Type.—The second limonite product of tetrahedrite origin, found chiefly in association with pyrite, consists of highly coagulated aggregates of the dully resinous granules already described. Where tetrahedrite greatly predominates, contour boxwork is prominent, and the coagulated particles merely form a thick coating on the wall which tends to close up cellular space locally. Where pyrite largely predominates, contour boxwork is partly obliterated, and the picture is rather that of scattered bunches of hieroglyphics embedded in the coagulated mass.

The product of ordinary mixed pyrite-tetrahedrite derivation may be distinguished from that of overwhelming pyrite derivation by the fact that where appreciable tetrahedrite was present (1) the product possesses an indistinct, sandy texture in contrast with the usual semi-vitreous surface and submetallic luster of the pyrite product; (2) the sandy coagulated aggregates comprise many dully resinous but distinctly formed limonite particles, with

FIG. 8. Coagulated type of limonite derived from tetrahedrite in the presence of abundant pyrite. Note in upper half of picture how the contour boxwork is coated over and locally largely obliterated by the coagulated limonite granules. White incrustations in lower half of picture consist of antimony oxides. Lake City, Colorado. × 4.5.

usually numerous scattered, fine, glistening embedded granules—in contrast with the "run together," smeary mass of pyrite origin in which ragged, rounded cells and finally nodular crusts merge indefinitely into each other; (3) in the tetrahedrite product are embedded at least occasional bunches of hieroglyphic or contour cellular structures (see Fig. 8), which are wholly absent in the pyrite product; (4) in most (but not all) cases the product derived from tetrahedrite carries scabs or fracture fillings of antimony oxides.

With great preponderance of pyrite in a fine-grained mixture the coagulated aggregates derived from tetrahedrite may conceivably merge into the smeary-crusted pyrite type, and possibly become indistinguishable from the latter. But such a condition has not thus far been observed; for tetrahedrite upon oxidation, even when of small occurrence, usually leaves an indelible record behind.

One other point may be noted: all limonite derived from tetrahedrite thus far observed—both contour boxwork and the coagulated type—has a characteristic chocolate to very deep brown color, the latter predominating. Those colors are not characteristic of limonite derived from pyrite. But color in limonite is governed by so many variables that the colors named must be regarded only as a general clue, to be substantiated by contour boxwork structure and by other more dependable physical characteristics.

FIG. 8. Coagulated type of limonite derived from tetrahedrite in the presence of abundant pyrite. Note in upper half of picture how the contour boxwork is coated over and locally largely obliterated by the coagulated limonite granules. White incrustations in lower half of picture consist of antimony oxides. Lake City, Colorado. × 4.5.

INFLUENCE OF GANGUE.

It has not been observed that any of the five limonite types derived from bornite predominate in either quartz, feldspar, or limestone gangue, except as noted for relief limonite. It therefore does not seem likely that neutralizer from the gangue is important in the formation of any except the relief type, and may not be fundamental there. In the formation of the caked limonite crusts, however, importation by ground waters of clay impurities, probably largely in colloidal form, seems a necessary condition.

Neither has either of the limonite types derived from tetrahedrite been found to favor quartz, feldspar, or limestone

gangues. But in observations thus far made the antimony oxide incrustations have been found in greater abundance in limestone areas.

CHEMICAL CONSIDERATIONS.

Bornite.—Bornite does not possess sufficient sulphur to dissolve itself completely. Unless acid from associated oxidizing pyrite or from other external source becomes available, complete oxidation of bornite does not occur.

The following reactions probably take place:

(1) $Cu_5FeS_4 + 18\frac{1}{2}O = 4CuSO_4 + CuO + \frac{1}{2}Fe_2O_3$.

(2) $CuO + H_2SO_4 = CuSO_4 + H_2O$.

Since 1 py is equivalent to $\frac{1}{2}H_2SO_4$, 2 py would be needed for all the copper of bornite to go into solution. $\frac{1}{2}Fe_2O_3$ would remain within the cavity.

(3) $\frac{1}{2}Fe_2O_3 + 1\frac{1}{2}H_2SO_4 \rightleftharpoons \frac{1}{2}Fe_2(SO_4)_3 + 1\frac{1}{2}H_2O$.

On the same basis, 3 additional py would be needed for all the iron from bornite to be exported, so that no limonite remained within the cavity.

In other words, for bornite to oxidize completely, the theoretical ratio would be 2 py: 1 bn (or greater proportion of pyrite); ½ mole of Fe_2O_3 would be precipitated within the cavity as limonite. For all the iron to be exported, so that no limonite remained within the cavity, the theoretical ratio would be 5 py: 1 bn (or greater proportion of pyrite).

Field observation corroborates these assumed reactions and ratios to the extent that (1) pure bornite, independent of strongly acid-yielding sulphides or of external acid attack, has not been found to oxidize completely. (2) Where complete oxidation has taken place, an excess of pyrite usually has prevailed. (3) With complete oxidation a varying amount of indigenous limonite remains unless a great preponderance of pyrite existed; the amount of limonite ordinarily decreasing with increase in proportion of pyrite. (4) Where cavities formerly occupied by bornite are wholly free of limonite, a great preponderance of pyrite (or its equivalent in acid-yielding sulphide) was present.

The theoretical ratios above stated therefore are probably not far from correct. But, as discussed under Tetrahedrite below, hydrolysis of ferric sulphate during the oxidation may somewhat reduce the proportions of pyrite needed below those shown in the theoretical ratios. More checking against field evidence is needed before a positive statement in the matter is justified.

The chief points to bear in mind are: (1) that bornite is likely to oxidize completely only in the presence of excess pyrite; (2) that where bornite has oxidized completely, the cavity is likely to retain limonite precipitates unless pyrite was present in overwhelming amount; (3) that pyrite in association with bornite is not ordinarily present in overwhelming amount; so that one or more of the five limonite types of bornite derivation above described usually remain in the cavity to denote the bornite's former presence.

Tetrahedrite.—Tetrahedrite, like bornite, possesses insufficient sulphur to dissolve itself completely. Unless acid from associated oxidizing pyrite or other external source becomes available, complete oxidation does not occur.

In the case of tetrahedrite the following reaction probably takes place:

$$(4) \quad 4Cu_2S.Sb_2S_3 + 32O = 7CuSO_4 + Sb_2O_3 + CuO.$$

As in the case of bornite, this leaves CuO unsatisfied. Since 1 py is equivalent to $\frac{1}{2}H_2SO_4$, 2 py would be required to complete the oxidation, thus:

$$(2) \quad CuO + H_2SO_4 = CuSO_4 + H_2O.$$

In the case of tetrahedrite less field evidence has been collected to substantiate these assumptions than in the case of bornite and the other common copper sulphides. But in the field it has been observed that resistance of tetrahedrite to complete oxidation ordinarily coincides with little pyrite in or near the tetrahedrite occurrences; that complete oxidation usually coincides with more abundant pyrite (or its equivalent in acid attack) for the deposit as a whole, where conditions for thorough leaching are otherwise favorable. To this extent the theoretical ratio is corroborated.

Since tetrahedrite carries no iron, iron salts must be supplied from an outside source during the oxidation before limonite can form. That the limonite does form, and remain conspicuously as an indigenous product in most instances, is attested by abundant field evidence.

Hydrolysis of ferric sulphate derived from oxidizing pyrite suggests itself as a ready source of the iron; thus:

(5) $FeS_2 + \frac{1}{2}H_2O + 7\frac{1}{2}O = \frac{1}{2}Fe_2(SO_4)_3 + \frac{1}{2}H_2SO_4$.

(3) $\frac{1}{2}Fe_2(SO_4)_3 + 1\frac{1}{2}H_2O \rightleftharpoons \frac{1}{2}Fe_2O_3 + 1\frac{1}{2}H_2SO_4$.

The free acid liberated might in turn reduce the proportion of pyrite needed in the sulphide body to effect complete oxidation of the tetrahedrite. This is the condition suggested on page 576, where an analogous case was considered for bornite, and where it was stated that less pyrite than shown in the theoretical ratios might be needed, as a result of the ferric sulphate hydrolizing.

Various considerations based on field evidence suggest that hydrolysis of ferric sulphate does not proceed uninterruptedly, nor does it ordinarily proceed to completion in any given case during oxidation of the sulphides. As a consequence, it probably does not constitute the sole, direct source of the iron that enters into the limonite-making reactions. By the same reasoning, hydrolysis of ferric sulphate probably does not greatly reduce the proportions of pyrite needed below those shown in the theoretical ratios for complete oxidation of bornite and tetrahedrite, though some reduction seems probable;—both of which assumptions are well supported by field evidence.

A previous paper touches upon the probable source of the supergene silica which enters into the composition of limonitic jasper in ordinary limonite boxwork,[8] and suggests as a source the silica carried either in solution or in colloidal form by circulating ground waters that traverse the deposit during oxidation. Such waters also often carry iron in notable amounts in mining regions, not only as ferric and ferrous sulphate, but in other

[8] ECON. GEOL., vol. 24, no. 8, December, 1929.

forms.[9] Irrespective of the form in which it may be carried at the time of precipitation, the imported iron of circulating ground waters probably provides an important percentage of the total iron entering into the composition of ordinary limonite outcrops. Iron supply consequently may not be wholly dependent upon that furnished by admixed pyrite or other iron-yielding minerals in the specific area undergoing oxidation at the time.

Further field evidence is being collected, and laboratory experimentation is being conducted, to establish more positively the facts relating to oxidation of tetrahedrite and the formation of its limonite. At this time the chief points to bear in mind are: (1) that tetrahedrite, like bornite, is likely to oxidize completely only in the presence of appreciable, possibly excess, pyrite (or its equivalent in acid attack) for the deposit as a whole; (2) that having oxidized, tetrahedrite usually leaves indigenous limonite even though it carries no iron; (3) that the limonite types resulting from oxidation of tetrahedrite are so distinctive as not to be readily confused with limonite products of other origin.

The Sb_2O_3 of reaction (4) manifestly becomes the source of the colorless to pale yellow or white antimony oxides that commonly incrust the limonite masses, or deposit in the outcrop along fractures and depressions adjacent to the limonite. The low solubility of Sb_2O_3 explains its ready deposition in outcrops close to the leached tetrahedrite.

SUMMARY

1. Neither bornite nor tetrahedrite contains sufficient sulphur to dissolve itself completely. Associated pyrite, or other sulphur from an external source, is needed before complete oxidation of either sulphide takes place.

2. Field evidence has not established definitely the proportions of pyrite needed to effect complete oxidation of bornite and tetrahedrite in nature. An excess of pyrite is probably needed in either case, and the theoretical ratio of 2 py : 1 bn in the case of bornite is presumably not far from correct. In the case of

[9] E. S. Moore, and J. E. Maynard: "Solution, Transportation, and Precipitation of Iron and Silica." ECON. GEOL., vol. 24, no. 3, May, 1929.

tetrahedrite a similar ratio of 2 py : 1 tet is probable, but at this time is less firmly established from field data.

3. Hydrolysis of ferric sulphate during the oxidation liberates acid, and may slightly reduce below the theoretical ratio the proportion of pyrite needed for complete oxidation of the bornite and tetrahedrite.

4. Field evidence shows that an overwhelming proportion of pyrite is needed to prevent formation of indigenous limonite after bornite. Such overwhelming proportion is not usual. This in part explains why leached bornite nearly always leaves indigenous limonite. Field evidence likewise shows that tetrahedrite usually leaves indigenous limonite, regardless of proportions of pyrite or other sulphide present, and even though tetrahedrite itself carries no iron.

5. Five limonite types derived from the oxidation of bornite have been identified and described. Of these a boxwork, suggesting in pattern the spherical triangle, and called triangular boxwork, is the most distinctive. To some extent it is usually present in each of the other types.

6. Leached outcrops derived from bornite generally carry a greater or less amount of "relief" limonite—a characteristic product, ochreous-orange in color, with a soft, velvety texture on fresh surfaces—which further aids in their identification.

7. Two limonite types derived from the oxidation of tetrahedrite have been identified and described. One, a long, deep-celled, abruptly angular structure—in cross section suggesting the contour map of a steeply mountainous region, and called contour boxwork—is the more distinctive, and is the most easily recognized limonite type derived from any of the copper sulphides. To some extent it is present in the second, more aggregated and less striking, limonite product of tetrahedrite derivation, aiding in the latter's identification.

8. Leached outcrops derived from tetrahedrite usually (but not always) carry local incrustations of antimony oxides that assist in the identification.

MECHANICAL ANALYSES OF SEDIMENTS BY CENTRIFUGE.[1]

PARKER D. TRASK.

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INTRODUCTION.

THE desired object of mechanical analyses of sediments is to ascertain the size distribution of the constituents. The various procedures of analysis are all based on Stokes' law which governs the rate of fall of particles through a liquid, and they have been summarized ably by Oden,[2] Rubey,[3] and Olmstead, Alexander and

[1] This paper contains results arising from an investigation on "The Origin and Environment of Source Sediments," listed as Project 4 of American Petroleum Institute Research. Financial assistance in this work has been received from a research fund of the American Petroleum Institute donated by Mr. John D. Rockefeller. This fund is being administered by the Institute with the cooperation of the Central Petroleum Committee of the National Research Council.

[2] Oden, Sven, "Methods to Determine the Size Distribution of Soil Particles," International Soil Science Conference, Rome, 1924, Sec. 1–A, No. 5.

[3] Rubey, W. W. "Lithologic Studies of Fine-grained Upper Cretaceous Sedimentary Rocks of the Black Hills Region, U. S. Geol. Surv. Prof. Paper, 165–A, pp. 14–31, 1930.

Middleton.[4] According to usual practice, the constituents are dispersed, the sands decanted and sieved, and the finer particles separated into groups by any of several methods, of which perhaps, pipetting is most used, or a complete size distribution is obtained by determining the increase of weight of particles that settle, with time. The good and bad points of these methods have been well discussed by previous workers, but they are all subject to one fundamental objection,—they are not practicable for measuring the size distribution of particles smaller than one, and usually, two μ. This is due chiefly to the great length of time needed for the smaller constituents to settle through a liquid under the influence of gravity. For example, it takes eight hours for particles of two μ to sink through ten centimeters of water at 20° C., and thirty-two hours for constituents of one μ.

The centrifuge has long been used to increase the rate of settling for the purpose of separating the silts from clays by decantation,[5] and Svederup and Nichols[6] have employed it to determine the dimensions of colloidal particles of submicroscopic size; but the writer has not seen reference to its use in facilitating analyses of sediments by the Oden method. This paper describes such a procedure, which is rapid and gives complete size distribution of particles down to any desired dimension, no matter how small.

The writer is indebted to Lauriston C. Marshall for criticism of this article from the viewpoint of a mathematician and physicist. Acknowledgment is due J. P. Koontz and F. B. Walcott for aid in standardizing the method.

DESCRIPTION OF THE METHOD.

Preliminary Treatment.—The method consists of separating the sands by decantation, and observing the increase in weight

[4] Olmstead, L. B., Alexander, L. T., and Middleton, H. E., "A Pipette Method of Mechanical Analyses of Soils Based on Improved Dispersion Procedure," U. S. Dept. Agric., Tech. Bull. No. 170, 1930.

[5] Briggs, L. J., Martin, F. O., and Pearce, J. R., "Centrifuge Method of Mechanical Analyses," U. S. Dept. Agric. Bur. Soils. Bull. 24, 1904.

[6] Svederup, T., and Nichols, J. B., "Determination of Size and Distribution of Particles by Centrifugal Methods," *Jour. Amer. Chem. Soc.*, vol. 45, pp. 2910–2917. 1923.

of the remaining constituents as they accumulate during successive intervals of centrifuging. By using a centrifuge with a capacity of four tubes, one may save much time by analyzing the samples in sets of four. Also, a special mimeographed form facilitates recording the notes. The centrifuge tubes are the conical, graduated A. S. T. M. oil centrifuge tubes of the Goetz type. They have a capacity of 100 cubic centimeters and taper downward to a narrow, cylindrical portion in which the sediment accumulates. This collecting chamber has an internal diameter of about eight millimeters, a capacity of about three cubic centimeters, is graduated to tenths of cubic centimeters, and may be read to hundredths. As the calculation of the size distribution depends upon the distance the particles fall, computation is facilitated by chosing tubes of essentially the same dimensions.

For dispersing the particles and separating the sands, standard procedure is followed. A six gram charge is dried at 105° C., weighed, soaked in distilled water for 24 hours, rubbed well with rubber pestle under water in a porcelain mortar, shaken overnight with 80 cubic centimeters of N/24 sodium carbonate, transferred to a decantation tube, and decanted to remove particles finer than sand (50 μ). The sediments are shaken in 35 mm. pyrex tubes, 22 cm. long, and closed at both ends by rubber stoppers. This permits of easy transfer of particles to decantation tube, as sand grains are readily washed out from a straight-walled open tube. The decantation tube is composed of a cylindrical barrel, which by means of a ground joint, fits firmly into a small cup. After decantation, the cylinder is removed from the cup, which permits the sands to be easily washed out.[7]

Determination of Size Distribution.—The size distribution of the constituents finer than sand is ascertained by plotting the accumulated weight against time, as in the Oden method; but as the particles fall under the influence of centrifugal acceleration, the rate of settling varies with the square of the angular velocity of the centrifuge. Thus, the time required to bring down con-

[7] Trask, P. D., "Sedimentation Tube for Mechanical Analyses," *Science*, N. S., vol. LXXI., pp. 441–442, 1930.

stituents of small size is much shortened. For example, particles of .4 μ will all settle out in 15 minutes at a speed of 2,500 revolutions per minute, compared with 200 hours by gravity. It is convenient to increase the velocity of the centrifuge as the particles to be brought down become smaller in size, but in order to ascertain the size distribution of the constituents, it is necessary to plot the entire accumulation of the sediment on the basis of a constant angular velocity and the same distance of fall.

A continuous curve is not procured as by the Oden automatic balance, but several points on that curve are ascertained by determining the weight of the sediment that settles out during the interval that particles of certain arbitrarily chosen diameters sink the specified distance through the suspension at the standard constant speed of the centrifuge. One can make as many determinations as he desires, but experience has shown that ordinarily a satisfactory weight-accumulation curve can be plotted on the basis of the respective times required for particles of 20, 10, 5, 2, 1, and .4 μ to fall the designated distance at the specified angular velocity. The weight of the sediment corresponding to 5, 2, 1 and .4 μ is ascertained from 100 cc. aliquots of the silt-clay suspension resulting from decantation of the sands,—one aliquot for each determination. After the proper amount of centrifuging (Table 1), the volume of the sediment is noted, the supernatant suspension is drawn or poured off, and the sediment transferred to an evaporation dish, dried and weighed. Flocculation occurs occasionally during centrifuging, but generally it may be eliminated by adding a little sodium carbonate solution to the suspension.

The intervals of centrifuging and the speed required to bring down all particles of the desired size from the suspension are shown in Table 1. In performing the analysis one follows the times for T_a, T_c, and T_d shown in this table for each of the six centrifuge intervals, noting that the first three are successive periods of centrifuging of one aliquot and that each of the last three represents a separate aliquot.

In order to estimate the quantity of material in suspension after all particles finer than .4μ have been brought down, before the

sediment is removed for drying a small portion of the supernatant suspension is pipetted from a short distance above the sediment, transferred to a vial, and compared in translucency with a series of standard suspensions of known content of similar-sized constituents.

Relation of Volume to Weight.—At the time the work was commenced it was hoped that the volume of material settling out could be used as a measure for the weight, but it was found that the weight-volume ratio varies greatly in different samples (from .42 to 1.18), and considerably in individual samples for particles of clay size. However, in any particular sediment it is practically constant for constituents of silt dimension (5–50 μ). Thus the weight of material that accumulates while particles of 20 and 10 μ are falling the required distance may be ascertained by multiplying the corresponding volume by the weight-volume ratio for the 5 μ fraction for that particular sample.

Regulation of Centrifuge.—As variations in the velocity of the centrifuge materially influence the results, it is desirable to use a constant speed motor. The usual type of centrifuge powered by an A.C. motor built around the axis of rotation is unsatisfactory from two standpoints,—first, the velocity of the centrifuge, although constant for short intervals, varies from day to day and as the motor becomes warm; and second, the heat from the motor hinders the maintenance of a constant temperature in the suspension. However, if one measures the velocity during each interval of centrifuging, fairly satisfactory determinations can be obtained by applying the proper correction for the speed. However, more accurate results can be procured by connecting the axle of the centrifuge to a constant speed D.C. motor by a pulley. By means of the proper combination of different-sized pulley wheels, the centrifuge may be maintained at any desired speed. In this manner, errors caused by variation in velocity are eliminated, the four different speeds required by the procedure of analysis are obtained, a short period of acceleration is produced, and heat from the motor does not affect the temperature of the suspension.

As the viscosity of the dispersing medium varies with the tem-

perature, it is essential that the suspension be maintained at a constant temperature while it is being centrifuged. This may be accomplished by forcing air through the centrifuge while it is in motion.[8]

As the calculation of the size distribution of the particles depends upon a constant angular velocity, corrections must be applied for the intervals during which the motor attains full speed and comes to rest after the current has been turned off. If the acceleration of the angular velocity during these starting and stopping intervals is constant, the calculation is simple, but if it is variable, the computation becomes complicated. Consequently it is desirable to produce a constant acceleration and to make the starting and stopping periods as short as possible.

The D.C. motor and pulley arrangement produces a rapid and practically uniform acceleration; or if one uses an A.C. motor built around the axle of the centrifuge, satisfactory acceleration may be procured by applying the full force of the current until the desired velocity has been attained and then throwing in the resistance necessary to maintain that speed.

The instrument is stopped by gripping a brass continuation of the axle. This extension of the axle protrudes through a hole in the protective cover of the centrifuge and consists of a ½ inch brass rod that replaces the nut which fastens the centrifuge head to the axle. By holding a cloth in one's hand, one soon learns to apply the proper pressure to stop the apparatus in the desired time. Measurements have shown that the acceleration is practically constant during starting and stopping, and for the short intervals used, no significant error is produced.

Summary.—In order to facilitate the description of the method, the procedure may be summarized as follows: the samples are dispersed; the sands decanted; the volume of the silt-clay suspension noted; 100 cc. aliquots of the silt-clay suspension from each of four samples transferred to centrifuge tubes, accelerated to speed of 360 r.p.m., run at that velocity for 17.5 seconds, decelerated in 1.5 seconds; the volume of sediment observed; the aliquots

[8] See Svederup and Nicols, *op. cit.*

again accelerated, run at speed of 360 r.p.m. for 54.5 seconds, decelerated in 1.5 seconds; the volume read; the same aliquots accelerated to 900 r.p.m., run at this velocity for 33 seconds, decelerated in 4 seconds; volume recorded; the sediment transferred and weighed; a second series of aliquots placed in centrifuge tubes, accelerated to 1,800 r.p.m., run at that velocity for 69 seconds, decelerated in 8 seconds; the volume read; the sediment transferred and weighed; a third series of aliquots similarly treated, except that the period of running at speed of 1,800 r.p.m. is 291 seconds; a fourth series of aliquots accelerated to 2,520 r.p.m., run at that velocity for 937 seconds, decelerated in 11 seconds; the volume recorded; a small portion of the supernatant suspension removed for estimation of amount of material remaining in suspension; and the sediment transferred and weighed.

THEORETICAL CONSIDERATIONS.

General Remarks.—The rate at which the constituent particles fall through water is of greater importance in interpreting the manner of deposition of the sediments than the size of the particles. For example, in beach sands, the diameter of the mica flakes as observed on the stage of a microscope is considerably larger than that of the sand grains; but the settling velocities are of the same order of magnitude. Fortunately, analyses based on Stokes' law give the settling velocity rather than the observed diameter. However, as it is more convenient to visualize the nature of sediments upon the basis of diameter of particles rather than of the rate at which they fall, the settling velocities are customarily expressed in terms of diameter of spherical particles of specific gravity of 2.6. This affords a practicable basis for comparing the manner of deposition of different sediments, and also permits of comparisons with the sand fractions which are measured on the basis of diameter, by sieving.

General Mathematical Basis.—Under centrifugal acceleration [9] the force applied to cause movement in fluids is

$$\frac{4\pi r^3(d_1 - d_2)\omega^2(x + a)}{3}$$

[9] See Svederup and Nichols, *Op. cit.*

and the frictional force resisting movement is $6\pi\eta r(dx/dt)$ where η is the viscosity, r the radius of a spherical particle, dx/dt the velocity of fall, d_1 and d_2 the density of the particles and the dispersing medium respectively, ω the angular velocity, a the distance of the particle from the axis of rotation before falling, and x the distance of fall. Equating these two relationships and arranging for integration, one has

$$r^2 \int_0^T dt = \frac{9\eta}{2\omega^2(d_1 - d_2)} \int_0^x \frac{dx}{x + a}. \tag{1}$$

From this it follows that

$$r = \frac{1}{\omega} \sqrt{\frac{9\eta \ln \frac{x + a}{a}}{2(d_1 - d_2)T}}. \tag{2}$$

As η, d_1 and d_2 are assumed to be constant this equation may be written

$$r = \frac{K_1}{\omega} \sqrt{\frac{\ln \frac{x + a}{a}}{T}}. \tag{3}$$

It follows from this equation that the relative rate of fall of particles of different size is the same no matter what the speed of the centrifuge. In other words, if a particle has fallen distance X_m in time T_m at angular velocity ω_m, it can be considered as having fallen the arbitrarily chosen standard distance X_s at the specified angular velocity ω_s in time T_p. Thus $r = K/\sqrt{T_p}$ and T_p is the time to be plotted against the weight in ascertaining the size distribution. This is the same formula used in the Oden method, but the constant is different.

During the time T_1 that particles of radius r_1 are falling distance X_s at velocity ω_s, a fraction of the constituents with radii less than r_1 have also settled out. If W_1 be the weight of all the sediment that accumulated during interval T_1, the tangent, dW/dt, to the weight accumulation curve at point, T_1, W_1, will represent the rate of fall of all particles still remaining in suspension. If $T = O$, W_0, be the intercept of this tangent on the Y-axis,

$W_1 - W_0$ is the weight of the particles smaller in radius than r_1 that settled out during time T_1, and W_0 is the weight of *all* particles in the original sediment larger than r_1. By means of a series of tangents, a corresponding number of points forming the basis for the size distribution curve are ascertained.[10]

As the time varies inversely with the square of the diameter, long intervals produce only slight changes in the size of small particles that settle out. It therefore becomes practicable to plot the weight accumulation curve in three parts, and to replace the standard time T_p by three time ratios, R_1, R_2 and R_3 (see Table 1). For convenience in plotting, $R = 2.52T_p = 6R_2$, and $R_2 = 25\ R_3$. In this way differences in the slope of the weight accumulation curve, in other words in the rate of fall, become apparent, thus facilitating the drawing of the tangents. The diameters corresponding to the various time ratios may be read directly from the graphs, by superposing a specially prepared scale showing the relation of diameter to the plotted times. The diameter-time scale for the first curve depends upon the relation $D = 54.8\ \mu/\sqrt{R_1}$, for the second, $D = 22.4\ \mu/\sqrt{R_2}$, and for the third, $D = 4.47\mu/\sqrt{R_3}$.

Formula for Accelerating Centrifuge Velocity.—Equation (3) shows the relation of settling time on the basis of a constant angular velocity, ω, but as it is impossible to run the centrifuge at a constant velocity from start to finish, a correction must be applied for the intervals during which it attains its maximum speed and while it is coming to rest. If the increase in velocity of the centrifuge, $d\omega/dt$, is constant, it will be equal to $2\pi N/T_a$, where N is the final number of revolutions per second and T_a the acceleration period. By integration, $\omega = 2\pi Nt/T_a$. Substituting this value for ω in equation (1) and rearranging, we have

$$\frac{4r^2\pi^2N^2}{T_a^2}\int_0^t t^2dt = \frac{9\eta}{2(d_1 - d_2)}\int_0^x \frac{dx}{x + a}.$$

[10] See Rubey, W. W., *op. cit.*, p. 24. Calbeck, J. H., and Harner, H. R., "Particle Size and Distribution by Sedimentation Methods," *Ind. and Eng. Chem.*, vol. 19, pp. 58–61, 1927.

Integrating,

$$\frac{4r^2\pi^2N^2t^3}{3T_a^2} = \frac{9\eta}{2(d_1 - d_2)} \ln \frac{x + a}{a},$$

but

$$\frac{4\pi^2N^2t^2}{T_a^2} = \omega^2.$$

Substituting and rearranging,

$$r = \frac{\sqrt{3}}{\omega} \sqrt{\frac{9\eta \ln \frac{x + a}{a}}{2(d_1 - d_2)T}}.$$

This equation differs from equation (2) which expresses the relation for constant angular velocity only by the factor $\sqrt{3}$. Thus, if T_a and T_d are the respective acceleration and deceleration intervals, and ω_1 the final angular velocity attained, the position of the particles would be the same as if the centrifuge had gone at constant velocity ω_1 for $T_a/3$ and $T_d/3$ seconds.

Thus, if the distance of fall is X_s, and T_c represents the time during which the centrifuge ran at constant speed,

$$r = \frac{K_2}{\omega_1 \sqrt{\frac{T_a}{3} + T_c + \frac{T_d}{3}}} = \frac{K_2}{\omega_1 \sqrt{T_t}}. \qquad (4)$$

This means that the relative position of the particles after accelerating constantly for T_a seconds, running at constant speed ω_1 for T_c seconds, and decelerating for T_d seconds is the same as if the centrifuge had run at constant speed ω_1 for T_t seconds.

If the insignificant settling while the volume is being read is ignored, the size of particles that will have fallen distance X_s at the end of centrifuging at speed ω_2 with acceleration, constant speed and deceleration intervals of T_a', T_c', and T_d', respectively, will be

$$r = \frac{K_2}{\omega_2 \sqrt{T_r + \frac{T_a'}{3} + T_c' + \frac{T_d'}{3}}} = \frac{K_2}{\omega_2 \sqrt{T_t'}} \qquad (5)$$

where

$$T_r = T_t\left(\frac{\omega_1}{\omega_2}\right)^2.$$

Standard Conditions for the Analysis.—The values for the different intervals used in performing the analysis are given in Table 1. They are based on the standard conditions adopted

TABLE 1.

STANDARD CONDITIONS FOR CENTRIFUGAL ANALYSIS.

Diam. in μ	R.p.s.	T_a	T_c	T_d	T_t	T_r	T_p	R_1	R_2	R_3
20	6	1.5	17.5	1.5	18.5	—	2.96	7.5	—	—
10	6	1.5	54.5	1.5	74.0	18.5	11.9	30.0	5	—
5	15	4	33	4	47.5	11.9	47.5	120.0	20	—
2	30	8	69	8	74.0	—	296	—	125	5
1	30	8	291	8	296	—	1190	—	—	20
.4	42	11	937	11	945	—	7400	—	—	125

Explanation.

R.p.s., revolutions of centrifuge per second $= \omega/2\pi$.

T_a, acceleration interval in seconds.

T_c, time of running at constant speed ω.

T_d, deceleration interval.

T_t, time of centrifuging continuously at constant speed ω, which will produce the same result as was obtained under the conditions of the experiment.

$$T_t = \frac{T_a}{3} + T_c + \frac{T_d}{3}.$$

T_r, time representing distribution of particles at beginning of centrifuge interval.

$$T_r = \left(\frac{\omega_1}{\omega_2}\right)^2 T_t,$$

where ω_1 is the angular velocity during the preceding centrifuge interval and ω_2 the speed for the interval in question.

T_p, time basis for plotting weight accumulation curve.

$$T_p = T_t\left(\frac{\omega}{\omega_s}\right)^2,$$

where $\omega_s = 94.25$.

R_1, R_2, R_3, time ratios used in plotting weight-accumulation curve.

$$R_1 = 2.52T_p = 6R_2 = 150R_3.$$

for the method. The distance from the axis of rotation to the surface of the suspension, a, is 8 centimeters, the standard dis-

tance of fall, X_s is 12.3 centimeters, $d_1 - d_2$ is assumed to be 1.6, ω_s is 94.25, and as the temperature is kept at 20° C., η is .01. Therefore, the diameter of the particles

$$D = 2r = \frac{34.5}{\sqrt{T_p}}, \tag{6}$$

where T_p is the time basis for drawing the weight-accumulation curve, and equals $T_t(\omega/\omega_s)^2$.

If the motor one uses produces acceleration intervals other than shown for T_a in this table, in order that T_t have the value given in the table, it becomes necessary to change T_c.

The efficacy of formula (6) for computing the diameter of the constituents has been checked by microscopic observation of the diameter of particles settling during various intervals of centrifuging. Formula (5) for calculating the fall of constituents during the three successive intervals required to measure the silt fraction has been substantiated empirically by comparing the weight of the material brought down during one period of continuous centrifuging of length computed according to formula (4) with that procured during the three successive intervals used in the normal procedure of analysis.

Correction for Distance of Fall.—If the speed of the centrifuge is as indicated for the various intervals shown in Table 1, and the distance of fall of the particles is constant and equal to X_s, all that is necessary in constructing the weight-accumulation curve is to plot the weights as per cent. of total weight of suspended matter, and the time as the proper value for R_1, R_2, or R_3. However, the longer the interval of centrifuging, the greater is the accumulation of sediment in the bottom of the tube, and unless compacting be excessive, the less the distance the particles have to fall. Therefore, after each interval of centrifuging, the distance the particles can fall, X_m, is different. Consequently the time ratio must be multiplied by the factor

$$\frac{\ln \frac{X_s + a}{a}}{\ln \frac{X_m + a}{a}}$$

in order to represent the true conditions after each period of centrifuging.

Table 2 shows the value of this correction factor for different volumes of sediment. In computing this table, X_s is 12.3 centimeters and is the distance in the centrifuge tubes between the

TABLE 2.

CORRECTION FOR DISTANCE OF FALL OF PARTICLES.

Volume.....	.10	.50	1.00	1.50	2.00	3.00	4.00	5.00
Factor.....	.96	.99	1.04	1.10	1.16	1.32	1.42	1.52

graduation marks for 100 and 0.55 cm. As an error of four per cent. in the time produces an inaccuracy of only two per cent. in the calculation of the diameter of the constituents, the correction can be ignored for volumes less than one cubic centimeter. This materially shortens the labor of computation, as 90 per cent. of the volumes are less than one cubic centimeter. Similarly, it is not necessary to apply a correction for x to T_r (see Table 1).

EXPRESSION OF RESULTS AS PERCENTILES.

Histograms are often used to depict analyses of sediments, but usually lack of space prohibits the portraying of a large number. However, the size distribution may be satisfactorily described by percentiles. Usually the three quartiles, *i.e.*, the 25, 50 and 75 percentiles are sufficient, but occasionally it is of value to give the 10 and 90 percentiles. A percentile for the size-distribution of sediments may be defined as that fraction of the sediment which is composed of particles larger in diameter than the dimension given for that percentile. Thus, if the three quartiles were 15, 4 and 1 μ respectively, it would mean that 25 per cent. by weight of the sample was composed of particles larger in diameter than 15 μ, 50 per cent. of the constituents greater than 4 μ, and 75 per cent. larger than 1 μ. This, with the percentage by weight of the sand, silt, clay and colloid gives an adequate picture of the sediment. Percentiles are especially advantageous for comparing deposits with each other, as they give exact numerical criteria for

classifying the size-distribution and obviate the necessity of such make-shift classifications as "sandy silt with considerable clay and some gravel." In fact, the median, *i.e.*, the 50 percentile may be used alone to designate the nature of the sediments. This permits the construction of contour maps showing the distribution of deposits on the basis of the median, or any other, percentile diameter. In this way, the manner in which sediments vary in composition may be portrayed satisfactorily, adequately and simply.

The percentiles are very readily obtained from the weight-accumulation curve by drawing tangents to the curve from points on the Y-axis corresponding to the desired percentile.[11] As the weight-accumulation graph, as plotted, represents that fraction of the sediment composed of particles smaller in diameter than 50 μ, the per cent. of sands must be subtracted from the desired percentile in making the computation. Thus, if ten per cent. of the sample were sand, the 25 percentile would be drawn from the point corresponding to 15 weight-per cent. on the Y-axis, and the 50 percentile from 40 weight-per cent. The diameter represented by the point of tangency is the desired percentile diameter. If more than 25 per cent. of the sample is sand, a graph based on the cumulative percentages of the various grades of sand is drawn on semi-logarithmic paper, the diameters being plotted logarithmically and the weights arithmetrically. The diameter corresponding to 25 weight-per cent. is taken to represent the first quartile.

The quartiles afford a basis for measuring the sorting and skewness of the sediment. If Q_1 and Q_3 are the first and third quartiles and M the median, the coefficient of sorting, $So = \sqrt{Q_1/Q_3}$, and the coefficient of skewness,[12] $Sk = Q_1Q_3/M^2$. A statistical study of 166 analyses of many different kinds of recent marine

11 Calbeck, J. H., and Harner, H. R., *op. cit.*

12 This formula for computing skewness was stimulated by C. K. Wentworth's paper on the third moment skewness in *Bull. Geol. Soc. Amer.* vol. 40, pp. 771–790, 1929, which appeared after this article had gone to press. The quartile skewness given in this paper and the third moment skewness described by Wentworth differ somewhat, but discussion of these two coefficients of skewness will be reserved for a later publication.

sediments shows that if So is less than 2.0, the deposit is well sorted, if it is above 4.5 it is poorly sorted, and if it is about 3.0 it is normally sorted.

CALCULATION OF TYPICAL SAMPLE.

In order to facilitate the description of the method, the data and calculations for a typical sample are shown in Table 3 and Fig. 1. All computations are made with slide rule and are based on the aliquot weights. The data permit expressing the results to three significant figures, but, as in all methods of mechanical analysis, the third figure is of doubtful accuracy. Consequently, it seems better to report the results to only two significant figures. Ordinarily the sands are separated into fractions by sieving, but as the sand sub-groups do not affect the calculations, they are not included in Table 3.

TABLE 3.

DATA AND CALCULATIONS OF SAMPLE 403 FROM MONTEREY BAY, CALIFORNIA.

Approx. Diam. in μ	Volume Aliquot	Weight Aliquot	Weight Per Cent.	R_1	R_2	R_3
20	.25 *	.177	19.7	7.5	1.3	—
10	.44 *	.311	34.7	30.0	5	—
5	.69 *	.487*	54.3	120.0	20	.8
2	1.04 *	.703*	78.2	—	130	5.2
1	1.17 *	.782*	87.2	—	—	21.2
.4	1.22 *	.824*	91.8	—	—	133
Fines	—	.008*	.9	Silt-clay volume.....630* cc.		
Sands	.418*†	.066	7.3	Total sample weight..6.00* gm.		
Total suspended matter	—	.898	100.0	Unaccounted.....0.056 gm.		

Sands (50 μ).....	7 per cent.	25 percentile.....13 μ	
Silt (5–50 μ).....	43 " "	50 "	5.0 μ
Clay (1–5 μ).....	39 " "	75 "	2.1 μ
Colloid (0–1 μ).....	11 " "	Water soluble.....	5.9 per cent.

The aliquot weight of the sands $= \dfrac{Weight\ of\ sands \times 100}{Silt\text{-}clay\ volume}$

$= .066$ gm. The total weight of the suspended particles is the sum of the .4μ fraction, the fines, and the sands $= .824 + .008$-

* Figures marked with asterisk are observed data, others are calculated.

† Total weight of sands. Figure placed in volume column for convenience.

$+ .066 = .898$ gm. The total weight of the aliquot should be

$$\frac{\textit{Total sample weight}}{\textit{Silt-clay volume}} \times 100 = .954 \text{ gm.}$$

This leaves an unaccounted residue of .056 gm., which is equivalent to 5.9 per cent. of the total sample weight. It is reported as water-soluble fraction. The weight-percentage of the fractions $=$

$$\frac{\textit{Weight of aliquot} \times 100}{\textit{Total weight of suspended matter.}}$$

Thus, the weight-percentage of the 5μ fraction $= .487/.898 \times 100 = 54.3$ per cent. The aliquot weights for the 20 and 10μ fractions are obtained by multiplying the aliquot volumes for these fractions by the weight-volume ratio for the 5μ fraction, which is $.487/.69 = .706$.

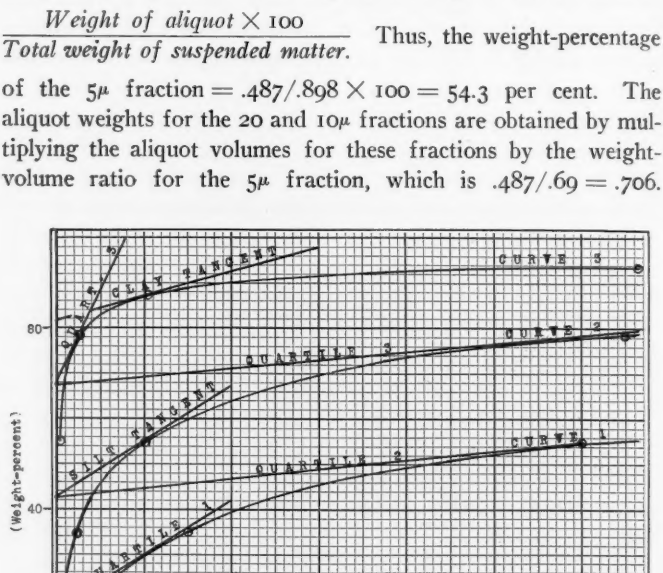

FIG. 1. Weight-accumulation curve for sample 403.

Therefore, the aliquot weight for the 20μ fraction is $.25 \times .706 = .177$ gm.

As the volumes of the clay aliquots in this sample are greater

than one cubic centimeter, the time ratios for these fractions should be multiplied by the proper correction factor. Thus, the time ratio for the 2μ fraction is $125 \times 1.04 = 130$.

The weight-accumulation curve is constructed in three parts by drawing smooth curves through the points determined by plotting the weight-percentages against the time ratios (Fig. 1). The percentage of silt (5–50μ) is determined by the intercept of the tangent from the point on curve 2 corresponding to 20 time units, and is 43 per cent. The difference between this intercept and that of the tangent from the point on curve 3 corresponding to 20 time units is the percentage of clay (1–5μ), *i.e.*, $82 - 43 = 39$. The percentage of colloids (0–1μ) is 100 minus the sum of the sands, silts and clay, which is 11 per cent. If one desires, he may subdivide the silt, clay or colloid groups by drawing additional tangents from appropriate points.

As 7 per cent. of the sample is sand, the tangents for the three quartiles are drawn from points on the Y-axis corresponding to 18, 43, and 68 per cent. By superposing the proper scale showing the relation of time to diameter, one finds the quartiles to be 13, 5.0, and 2.1μ respectively. As the median diameter is 5.0μ, the tangent for the second quartile coincides with the silt tangent. It so happens that in this particular sample the tangent for this percentile may also be drawn to curve 1, which it intercepts at the point corresponding to 5μ, which is the same diameter determined by its intercept on curve 2. Similarly, the third quartile gives a diameter of 2.1μ whether drawn to curve 2 or to curve 3.

VALUE OF METHOD.

Provided the centrifuge is run at constant speed and is started and stopped with uniform acceleration, the modification of the procedure of analysis by Stokes' law by increasing the rate of fall of particles by centrifugal action, adds no serious sources of inaccuracy to the fundamental errors inherent in all methods of mechanical analysis. However, it is conceivable that slight inaccuracies might arise from varying weight-volume ratios within the silt fraction, from imperfect mixing of the silt-clay suspension

before removing the aliquots, from the slight swirling action produced in the suspension as the centrifuge is stopped, and from error in constructing the weight-accumulation curve and in drawing the tangents. However, numerous duplications and tests have shown that individually these sources of error are of small magnitude. It is conceivable that they might be cumulative in some samples, but on the average they would more or less compensate for each other. In comparison with errors arising from imperfect dispersion,—a potential source of considerable inaccuracy in any method of analysis—they are of slight importance and therefore detract but little from the value of the method.

The percentage distribution of the constituents ordinarily is based on the weight of the sample as dried at 105° C. This does not represent the true sample weight because adsorbed water present in the sediment at time of weighing adds to the weight of the constituent particles. Consequently, an error is introduced in all percentage calculations based on this weight, especially in clay or colloid fractions determined by difference. In the method described in this paper, the inaccuracy due to adsorbed water is considerably diminished, if not almost eliminated, because the percentages are based on the total weight of suspended matter, ascertained from weighings of material dried as very thin films on evaporation dishes, which permits of effective drying.

The advantages gained by using the centrifuge facilitate greatly the procedure of analysis. The method is rapid—one person can determine and calculate the size distribution of particles finer in size than sands at the rate of four samples in two hours, and can finish about 30 complete analyses a week; it does not involve complicated apparatus; it gives the size distribution of particles rather than a segregation into a series of groups; it permits of the ready presentation of the results as percentiles; in contrast with a number of other methods, it gives the distribution of the particles actually in suspension, that is, the soluble constituents and adsorbed water are not included in the group representing the most fine-grained fraction of the sediment; and it determines the size distribution of the particles down to any desired size limit, no matter how small,—a feature lacking in almost all other methods.

SUMMARY.

This paper describes an application of the centrifuge to the procedure of mechanical analysis of sediments on the basis of Stokes' law. The method consists in decanting the sands, and determining the rate of increase in weight of the finer particles settling out, with time. This is accomplished by separating the suspension containing these finer constituents into a number of aliquots and ascertaining the weight of material that settles from each aliquot after centrifuging for definite times and at specified speeds. Curves, representing the rate of fall, are constructed by plotting the weight of the sediment that settled from the aliquots, against the proper values for the time. From these curves, both the size distribution of the constituents and the percentile diameters are readily obtained. The chief advantages of the method are: it is rapid; it does not involve complicated apparatus; it permits of presentation of the results as percentile diameters; and it gives the complete size distribution of the constituents down to any desired dimension, no matter how small.

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THE TEXTURE AND ORIGIN OF SOME BANDED OR SCHISTOSE SULPHIDE ORES.

W. H. NEWHOUSE AND G. F. FLAHERTY.

Introduction.

Sulphide orebodies showing banded, schistose or gneissoid structure, commonly occur as lenticular or tabular bodies in dynamo-metamorphosed rock, usually a schist, with an alignment of the orebodies and of the banded structure of the ore more or less parallel to the rock schistosity. The sulphides are chiefly those of iron, copper, zinc, and lead, that form alternating bands of pyrite or pyrrhotite and chalcopyrite, sphalerite, galena, and country rock. Quartz is nearly always present in some amount.

Numerous examples of the schistose, or gneissoid ores are known, of which the Blue Hill, Maine, deposits, Mandy orebody in Manitoba, Shasta County, California copper deposits, and those of Rammelsberg, Germany, are representative.

The origin of this banded structure has in some instances been ascribed to the dynamo-metamorphism[1] of a massive orebody which made the enclosing country rock schistose and caused a flowage in the ores that resulted in a segregation of individual minerals into parallel bands.

Many occurrences are considered as replacements[2] of the schistose rocks in which they occur, the banding being caused by preferential replacement of different bands of the schist by the several minerals.

The geological evidence bearing on the pre- or post-meta-

[1] Lindgren, W., and Irving, J. D., "The Origin of the Rammelsberg Ore Deposit," Econ. Geol., *6*, 303–313, 1911. Emmons, W. H., "Some Ore Deposits in Maine and the Milan Mine, N. H.," U. S. Geol. Survey Bull. 432, 1910.

[2] Bruce, F. L., "The Amisk-Athapapuskow Lake District," Canada Geol. Survey, Mem. 105, pp. 71–76, 1918. Hanson, George, "Some Canadian Occurrences of Pyritic Deposits in Metamorphic Rocks," Econ. Geol., *15*, pp. 585–587, 1920. Clapp, C. H., "Sooke and Duncan Map Areas, Vancouver Island," Canada Geol. Survey, Mem. 96, p. 389, 1917.

morphic age of such orebodies is not always sufficient to be conclusive.

With this in mind the writers have made a comparative study of the ores and their associated minerals, from a number of districts where the geological relations show clearly that the ores are of replacement origin, with those from some districts where the ores have been undoubtedly banded by flowage. Some mixed massive sulphide ores were experimentally deformed to give positive examples of plastic deformation for comparison.

The ores were studied in polished sections, chiefly by etching,[3] in order to reveal the crystal habit. The attempt was made to portray the crystal and mineral relations in the ores, which are determined in rocks by the petrographic microscope.

The results are set forth in this paper, together with a discussion on the origin of several orebodies of interest in this respect.

Textures of Banded Replacement Ores.

Ores from a number of different localities where the geological evidence points to an undoubted replacement origin were examined. Several typical localities have been selected for individual description.

Mammoth Mine, Shasta County, California.—The evidence that the Mammoth ores have formed by the replacement of sheared and somewhat schistose alaskite porphyry and in minor part of slate, is very convincingly set forth by Graton,[4] and need not be considered in this paper.

Banded ores from this mine consist of pyrite, sphalerite and chalcopyrite arranged in bands and irregular streaks. The sphalerite bands contain irregular streaks of chalcopyrite, and the chalcopyrite bands contain elongated masses of pyrite and sphalerite, the individual grains of which vary from .10 to .50 mm. in

[3] Schneiderhöhn, Hans, "Anleitung zur mikroskop. Bestimmung von Erzen," pp. 116–117, 1922. Chalcopyrite etch 2 cc. Conc. $K_2Cr_2O_7$ + 23 cc. H_2O + ½ cc. Conc. H_2SO_4. Time, 20 Min. Galena etch 1 cc. Conc. HNO_3 + 5 cc. H_2O. Time, ½ Min.

[4] Graton, L. C., "The Occurrence of Copper in Shasta County, California," U. S. Geol. Survey Bull. 430, pp. 71–111, 1909.

diameter. The pyrite is often fractured with chalcopyrite filling between and replacing the fragments and crystals. The chalcopyrite bands are composed of allotriomorphic non-elongated crystals which are commonly about .20 mm. in diameter.

The grain size is smaller in general than that displayed by the non-banded ores, of Sudbury, Ontario; Bisbee, Arizona; Rouyn, Quebec; and Terre Neuve, Haiti, West Indies.

The chalcopyrite crystals are quite strongly twinned with the twin bands occasionally bent. Quartz frequently forms radial aggregates around pyrite crystals and shows undulatory extinction with the crystals displaying a curved and twisted appearance, as has been noted also by Graton. The quartz with the sulphides does not show the elongation and parallel optical orientation which is common to the original quartz in schists.

Although there has doubtless been some slight deformation of the orebody as is shown by the bent twin bands and fractured pyrite, the lack of elongation and parallel orientation of the chalcopyrite and quartz crystals shows that there has been little flowage or distortion of the solid ores and thus is in harmony with the conception, based on geological grounds, that the ores have had their banding formed by preferential replacement rather than flowage.

United Verde Mine, Jerome, Arizona.—Some of the ore from the United Verde Mine displays rude banding of the chalcopyrite, pyrite, and black schist. This deposit has been formed by replacement according to Reber[5] and Lindgren,[6] the conclusion being based on good data.

The crystals of chalcopyrite show little or no twinning and no deformation nor elongation. The grain size in the specimens examined is about the same as that of the chalcopyrite from the Mammoth Mine, California (Fig. 5).

Tyee, B. C.—Banded ore from Tyee, B. C., that has been described as a replacement of schistose rocks[7] was examined and

[5] Reber, L. E., "Geology and Ore Deposits of the Jerome District," *Trans. Am. Inst. Min. and Met. Eng., 66*, pp. 14–16, 1922.

[6] Lindgren, W., "The Ore Deposits of the Jerome Bradshaw Quadrangle." U. S. Geol. Survey Bull. 782, pp. 1–78, 1926.

[7] Clapp, C. H., Canada Geol. Survey, Memoir 96, p. 389, 1917.

found to show features similar to those just described. The chalcopyrite is present as allotriomorphic crystals, which are strongly twinned, and with the twin bands bent and contorted. No elongation of the crystals was found in any of the sections examined and the size of the individual crystals approximates that of the previously described examples.

It appears that there has been some deformation of this ore but that it has been small in amount.

Experimental Work on the Deformation of Mixtures of Ore Minerals.

It is a well established fact that a number of the softer ore minerals may be deformed like plastic substances.

The evidence and data on this subject have been recently summarized by Buerger.[8]

In the present study, in order to supplement the previous work, it was deemed important to obtain data on deformation of ores containing more than one crystal, so some experiments were undertaken.

Specimens of massive ore containing a large percentage of chalcopyrite, some sphalerite, and a little pyrite from Tezhuitlan, Vera Cruz, Mexico, were cut to cylinders which would fit tightly into a heavy copper cylinder fitted with a steel plunger. This is a modified form of the apparatus used by Adams[9] in his work on the deformation of rock minerals. The apparatus was placed in a long column testing machine having a capacity of 100,000 pounds vertical load. The machine was set to feed .03 inch per minute. After the test piece of ore had deformed sufficiently to strongly bulge the retaining walls of the copper cylinder, the machine was stopped, and a polished section of the ore specimen was made. Several tests of this kind were run. The cylinder of ore was polished and examined by etching both before and after deformation.

[8] Buerger, M. J., "The Plastic Deformation of Ore Minerals," *Amer. Miner.*, *13*, pp. 1–17; 35–51, 1928. "Translation Gliding in Crystals," *Amer. Miner.*, *15*, pp. 45–64, 1930.

[9] Adams, Frank D., "Differential Pressure on Minerals and Rocks," *Jour. Geol.*, *18*, pp. 489–525, 1910.

The chalcopyrite was found to flow and some crystals became elongated approximately normal to the deforming pressure to a length two to three times their width. Many small fractures were also developed, doubtless in part due to the ore not exactly fitting the containing copper cylinder.

The sphalerite became fractured whereas the pyrite crystals were sheared by the movement of the chalcopyrite into thin plates which were arranged " en echelon " to each other, thus producing an elongated broken mass of pyrite.

The deformed test pieces clearly show the tendency to produce banding by stringing out masses of individual minerals into parallel bands, the softest by flowage producing grain or crystal elongation, the harder ones by shearing and linear distribution of the broken fragments.

Of much importance is the fact that the chalcopyrite crystals apparently developed a preferred orientation when thus elongated as was shown by the very similar degree of etch tarnish which they all gave after deformation. It has been pointed out before [10] that both galena and chalcopyrite are likely re-oriented on deformation.

Under external stresses sulphides may deform by fracturing or by plastic flowage. Certain sulphides such as chalcopyrite may twin when subjected to stress. Twinning may be produced in several different ways, the conditions necessary to produce it not being well understood.

Textures and Structures of Ores Banded by Flowage.[11]

Examples of ores which have been deformed to the extent that flowage has produced a gneissic or banded appearance have been described from Slocan, B.C.,[12] and Coeur d'Alene district, Idaho.[13]

[10] Buerger, M. J., *Amer. Miner., 13,* p. 46.

[11] Frebold, G., " Ueber die kinetische Metamorphose der Erze; eine grundsatzliche Untersuchung," Preuss. Geol. Landesanstalt Abt. f. Gestins—u. s. w. Untersuchengen mitt. H. 5, 44 pp., 1928. This paper gives interesting examples of deformed ores chiefly from the standpoint of mineral masses rather than crystals.

[12] Uglow, W. L., " Gneissic Galena Ore from the Slocan District, B.C.," Econ. Geol., *12,* pp. 643–662, 1917. Bateman, Alan M., " Notes on Silver-lead Deposits of Slocan District, B.C.," *Idem, 20,* p. 562, 1925.

[13] Waldschmidt, W. A., " Deformation in Ores, Coeur d'Alene District, Idaho," Econ. Geol., *20,* p. 577, 1925.

In ore from the Coeur d'Alene district broken masses and grains of sphalerite, pyrite, and tetrahedrite are strung out in broken fragments along irregular lines in the galena, giving the ore its banded appearance. These structures have been noted chiefly in the ores of the Hecla Mine, the Morning Mine, and the Star Vein. In the ores of the Star Vein, the banded structure is particularly well displayed, where sphalerite embedded in the galena in coarse aggregates, is drawn out in streaks, parallel to the galena flowage structure. Ore from parts of the Hecla vein show a roughly banded structure in the hand specimen.

FIG. 1. Schisted galena, Coeur d'Alene, Idaho. Deformation has by plastic flow produced parallel elongated masses. × 80.

The galena has a schistose appearance due to the elongation of crystals in one direction (Fig. 1). Galena is thus the flowage medium in which the other minerals have been strung out by the flowage, into streaks which are more or less parallel. Some of these embedded minerals may have been broken by the shearing force exerted upon them by the movement of the host galena; possibly the pyrite was so fractured. In order to learn whether the sphalerite had been deformed, an attempt was made to etch the small sphalerite masses included in the galena, but due to the

strong reaction of the galena with the reagent, no etching of the sphalerite was obtained. Larger masses of sphalerite free from galena were successfully etched, however, and the sphalerite was found to have a texture of small interlocking crystals from 0.01 to 0.03 mm. in diameter, the individual crystals showing strong polysynthetic twinning. From this evidence it may be concluded that some of the sphalerite was deformed, but not so as to cause noticeable elongation. Etching of the " steel galena " showed the deformed state of the galena crystals. The texture consists of a mass of parallel elongated ribbon-like crystals, the elongation being due to plastic deformation by slippage or gliding within the crystal.

The banding seen in the hand specimen is largely the result of flow lines in plastically deformed galena, and the drawing out of broken grains of sphalerite, tetrahedrite and pyrite along the flow lines of the galena.

Banded Ores of Disputed Origin.

Blue Hill, Maine.—A number of the New England ore deposits are banded, or schistose. Several of them, the most important of which are those at Blue Hill, Maine, and that at the Milan Mine in Coos County, New Hampshire, have been held to be regionally metamorphosed.[14]

Geological evidence has accumulated which disproves this view in regard to the Blue Hill ore deposits. This evidence will be briefly summarized, and the results of our microscopic study will be given in support of a post-metamorphic age. No new geological evidence bearing on the relations at the Milan Mine has been obtained but the microscopic study indicates that the ore resembles that of Blue Hill, a replacement of schist.

Lindgren[15] has recently called attention to the high temperature type of mineralization, and Gillson[16] has described in some

[14] Emmons, W. H., " Some Regionally Metamorphosed Ore Deposits and the So-called Segregated Veins," Econ. Geol., *4*, pp. 755–781, 1909.

[15] Lindgren, W., " The Cordierite-anthophyllite Mineralization at Blue Hill, Maine, and its Relation to Similar Occurrences," *Proc. Nat. Acad. Sci.*, *11*, No. 1, pp. 1–4, 1925.

[16] Gillson, J. L., " Contact Metamorphism of the Ellsworth Schist, near Blue Hill, Maine," Econ. Geol., *24*, pp. 182–194, 1929.

detail the contact metamorphism imposed on the schist by the later granite intrusion at Blue Hill.

The ore deposits occur in the Ellsworth schist (pre-Cambrian?) and in the schistose Castine (Cambrian?) formation.

Recent field work shows that one deposit of the same mineralogy as those in the schist occurs in the granite which is of questionable Devonian age.

The following facts relate the mineralization to the Devonian, or Silurian granite, which is later than the main regional metamorphism. The map of the mineral deposits [17] shows that they are clustered around the granite intrusion. Furthermore, a rude zonal arrangement of the minerals and metals in the various deposits is apparent, with the pyrrhotite, chalcopyrite deposits near the town of Blue Hill forming the central zone. The schist in which these veins occur is included between two granite masses, which doubtless accounts for the high temperature type of mineralization, as well as the associated contact metamorphism.

The Tapley Mine, which is about one mile west of the granite mass, has copper as the chief metal and contains a number of high temperature minerals, while beyond it at a distance of four miles from the granite is found the Cape Rozier mine, with a copper zinc mineralization and no high temperature minerals described as present. The other mines beyond the western and southern borders of the granite mass show lead and zinc, with some copper, in contrast to the central copper zone near Blue Hill village.

Of interest is the fact that many of the lower temperature minerals such as barite, sphalerite, chalcopyrite, galena, as well as pyrite and arsenopyrite of these veins, are found in deposits which are definitely later than the metamorphism and occur in places as fissure veins crossing the schistosity some miles northeast of Blue Hill. This mineralogy, which is very similar to that of the lead and zinc mines near Blue Hill, has been related to the granite intrusions by Emmons.[18]

Directly relating the Blue Hill mineralization to the granite

[17] Emmons, W. H., "Some Ore Deposits in Maine and the Milan Mine, New Hampshire," U. S. Geol. Survey Bull. 432, 1910.

[18] Emmons, W. H., U. S. Geol. Survey Bull. 432, p. 20, 1910.

intrusion is the presence of a mineralogically similar deposit in the granite at Blue Hill. This deposit has been called the Owen Lead Prospect, and is described by Emmons as a magmatic segregation of galena, pyrite, and chalcopyrite in the granite. More recent work has exposed a mineralization in the granite composed of chalcopyrite, galena, pyrite, sphalerite, pyrrhotite, and magnetite. These are the typical minerals of the nearby ore deposits in the Ellsworth schist and the Castine formation. Polished sections of the granite that contains these sulphides show that they are mainly arranged along incipient fracture zones in the granite and the thin sections show little attendant alteration of the granite minerals.

Sulphide veins at Blue Hill, in the Ellsworth Schist, in places cuts across the lamellæ of the schist. Particularly good examples of small cross-cutting veins were observed at the Twin Lead Mine. One of these small veins containing quartz, pyrite, and chalcopyrite cuts squarely across the schistosity. On the surface the pyrite appeared fractured, probably due to weathering, but specimens from a couple of inches beneath the surface reveal practically no fracturing under the microscope.

Numerous polished sections of ores from the several mines at Blue Hill show only a small amount of slightly fractured pyrite. There is no evidence of recrystallization, since the ores show only the normal time sequence of mineral introduction and only one generation of pyrite.

The texture of the pyrrhotite and chalcopyrite is the same as that found to be common in ores formed by replacement of schists. No elongation of crystals of either mineral parallel to the schistosity was found.

Finally, and more conclusive than the evidence afforded by the sulphides, is the habit of the quartz associated with the sulphides.

As is well known, quartz crystals of schists frequently show an elongation parallel to the schist laminæ, and also often a parallel optical or crystallographic orientation. The quartz grains in the Ellsworth schist commonly show both these features since they have been re-oriented in the regional metamorphism (Fig. 2).

The quartz associated with the ore minerals, which is undoubtedly of the same age as the sulphide mineralization, shows neither of these features common to the quartz in the unmineralized schist. The quartz crystals have the interlocking habit common to vein quartz and are larger than the quartz grains in the schist. They have been neither elongated, nor re-oriented by metamorphism (Fig. 3).

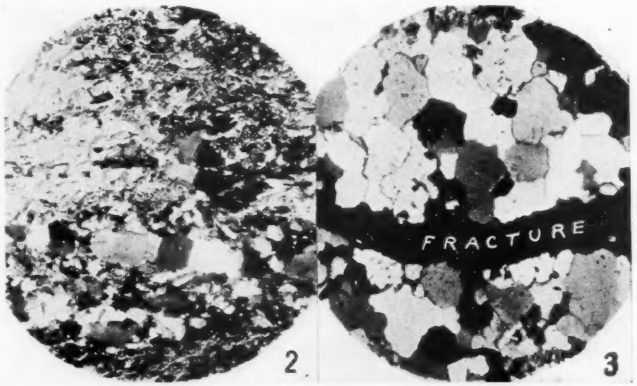

FIG. 2. Elongated quartz grains in the Ellsworth schist near vein, Blue Hill, Maine. × 20.

FIG. 3. Quartz in ore, Blue Hill, Maine, shows typical rounded crystals of quartz connected with the mineralization. These crystals have not been subjected to the pressure indicated in Fig. 2. × 20.

Milan Mine, Coos County, N. H.[19]—The two overlapping lenticular orebodies at this place strike and dip parallel to the schistosity of the country rock. Pinching and swelling in the orebodies is reflected in the enclosing schist, whose lamellæ are closely conformable to the outline of the orebody. The central mass of the orebody was of massive pyrite, but the outer parts had a distinctly banded structure, with parallel bands of sphalerite, pyrite, chalcopyrite, galena, and schist country rock.

[19] Emmons, W. H., Description of the orebody taken from U. S. Geol. Survey Bull. 432, p. 50 et seq., 1910.

It has been held that the ore deposition at the Milan Mine was earlier than the metamorphism that rendered the country rock schistose, and that the banded structure in the ore was due to crushing and flowage of the constituent minerals.

So far as the above description goes, it is typical of schist replacement ores. A central massive sulphide part of the orebody formed in a main shear zone, with less intense replacement on the borders of the mass along certain bands in the schist which produced the well banded ores showing residual bands of schist.

The banding in the ore specimens is like that of the undoubted replacement deposits in schist when it is examined in polished sections. The galena and sphalerite show the normal texture on etching that is displayed by the replacement ores, except that the galena in places occurs as slightly elongate crystals, and the sphalerite is much twinned although showing no elongation of crystals. The chalcopyrite has no elongation of crystal in most sections examined but a few show an elongation of about three times the width of the crystal. Bent polysynthetic twin lamellæ are present in the chalcopyrite.

The pyrite which occurs disseminated in sphalerite or as separate veinlets in the country rock in polished section either shows no shearing or breakage, or no more than is common to pyrite from many other districts.

It is evident from the above description that some slight deformation has taken place. No evidence of recrystallization later than the deformation of the minerals was found.

Comparing the data with the results obtained in the experimental work, the net elongation of the Milan orebody by flowage or crushing is at the most only a very few per cent. Quartz, which has entered with the sulphides, shows undulatory extinction but does not show a parallel elongation and optical orientation to the schist laminæ. Cordierite occurs as a wall rock alteration product; one hand specimen of schist is composed mainly of this mineral. In none of the thin sections examined did this mineral, which often is in certain bands of the schist with pyrite, show any notable deformation.

Mandy Orebody, Manitoba, Canada.—The Mandy ore deposit has been described by Bruce [20] and Hanson [21] as a replacement deposit formed along a shear zone in chloritic schist. The deposit is in the form of an irregular lens pitching steeply to the south, in a band of chloritic schist, which lies in massive greenstone. The lens is elongated along the general strike of the schists, and is believed to have formed by the replacement of the chloritic schist. A zone of finely banded chalcopyrite and sphalerite occurs in the central part of the orebody, and is bordered on one side by a zone of pyrite which runs along the hanging wall, and on the other side by a lens of pure chalcopyrite which, in turn, is bordered by a 12-foot zone of pyrite that runs along the footwall. The banded zone is one of predominent sphalerite but also contains much chalcopyrite interbanded in thin seams with similar seams of sphalerite. Pyrite is also present, and bands of country rock are fairly common. The banding is roughly parallel to the walls of the orebody. Hanson [22] states that some of the thicker bands are continuous for 50 feet along the strike, and that the thinner ones pinch out and new ones begin in a distance of 1 or 2 feet. Included lenses of schist are uncommon, but where they are present, the schistosity and elongation of the lenses are always parallel to the schistosity of the country rock.

Spurr [23] has given a different interpretation of the origin of this orebody.

According to this author: [24] The fine lines and bands of blende are so intimately interstreaked with the chalcopyrite, and the streaks are drawn out in such perfect parallelism, that the conclusion is that the structure is the result of flow, and that the ore could have been introduced in no other way than in plastic form, as an intrusive mass.

This idea is presented with a diagram showing the flow lines in the sulphides, which display (if this idea is considered) a

[20] Bruce, E. L., Canada Geol. Survey, Mem. 105, 1918.
[21] Hanson, George, Econ. Geol., 15, pp. 574–609, 1920.
[22] *Op. cit.*
[23] Spurr, J. E., "The Ore Magmas," pp. 110–122, 1923.
[24] *Idem*, p. 115.

disregard for the laws of flow of fluids and plastic substances (Fig. 4). If the sulphides had been intruded as a plastic, or fluid mass, the flow lines in the sulphides should conform to the outlines of the enclosing rock mass.

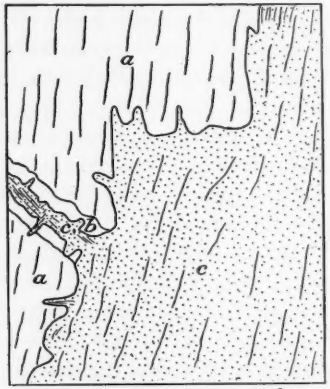

FIG. 4. Diagram of Ore relations, Mandy Mine, Manitoba. (Spurr, Ore Magmas, p. 115.) Shows essential parallelism of lines in main mass of ore (*c*) with enclosing schist (*a*). If (*c*) had been forced into (*a*) as a plastic mass the flow lines should parallel the walls of (*a*). Compare with the description of banding in relation to wall rock at Rammelsberg, Ger.

Instead of this the flow lines, as shown in the diagrams, in both ore and wall rock are mutually parallel which argues for a common origin. In view of Bruce's and Hanson's data and conclusions, the origin of such parallelism must be that the sulphides have retained the flow lines of the schist during the replacement.

Etching of the sphalerite bands in the Mandy ore was not very successful owing to the large quantity of admixed chalcopyrite. It was, however, found that the sphalerite is twinned to some extent.

The chalcopyrite has a fine-grained texture of interlocking often slightly elongated crystals having a diameter of 0.20 to 0.50

mm. The crystals show very little twinning and are quite undeformed. The texture, size and relations of crystals is typical of the other replacement ores discussed. Neither the chalcopyrite nor the sphalerite, therefore, have been severely deformed, and in harmony with the geological evidence it may be concluded that the fine banding and apparent flow structure do not owe their origin to flowage but are inherited from the replaced rocks.

Rammelsberg, Germany.—The structure and mineralogy of the copper deposit of Rammelsberg, near Goslar, Germany, has been briefly described by Lindgren and Irving,[25] and at greater length by a number of German writers. Ramdohr [26] has recently given considerable attention to the microscopic features displayed by the ores.

The deposit is enclosed more or less conformably in the Goslar slates of Middle Devonian age; the slates and the orebodies dip about 45° southeast. The slates have been considerably contorted and the orebody generally follows the contortions in the slates. Although several authors, in describing the Rammelsberg deposit, state that the outline of the orebody and its banded structure are absolutely conformable with the schistosity of the enclosing slates, Lindgren and Irving [27] find that while this is true in places, it is not characteristic of the deposit. In part it is quite unconformable to the stratification of the slate. The banded structure of the ore, however, faithfully follows the outline of the orebody, even in minute crumplings and crenulations in the small offshoots of the ore into the slates. Where the orebody cuts across the schistosity of the slates the ore banding still follows in detail the outline of the orebody. In all cases where the orebodies cut across the schistosity of the slates, the laminæ of the slates end abruptly against the ore, and continue in the same direction on the opposite side without showing the least distortion against the ore mass. The parallelism of the flow lines in the ore with the outline of the orebody harmonizes with the laws of flow

[25] Lindgren, W., and Irving, J. D., ECON. GEOL., 6, pp. 303–313, 1911.

[26] Ramdohr, Paul, *Neues Jahrb. f. Min. Geol. u. Pal.*, B. 1, Bd. 57, Abt. A, pp. 1013–1068, 1928.

[27] *Op. cit.*

lines produced in fluid, or plastic flow within a container. The contrast with the relations of flow lines at the Mandy orebody is most important.

Structure of the Ore.—The principal minerals of the ore are sphalerite, chalcopyrite, galena, pyrite and arsenopyrite. Extremely fine-grained intergrowths of sphalerite, chalcopyrite, and galena, are characteristic of the ore, a common structure showing intimate banding of sphalerite, chalcopyrite and galena, with sphalerite as the predominent mineral. In this structure the galena and chalcopyrite occur in gently curving streaks through the sphalerite, the streaks in places curving conformably about nodular inclusions of pyrite or barite. Some hand specimens exhibit an almost perfect parallel banding of sphalerite and chalcopyrite, the individual bands viewed macroscopically having straight parallel contacts continuous across the length of the hand specimens. Examination of the sphalerite bands under high magnification reveals swarms of minute masses of galena and chalcopyrite included in the sphalerite.

Lindgren and Irving liken the structure of the ore to that of a dynamo-metamorphosed rock, and state that the sulphides galena, sphalerite, and chalcopyrite have acted under pressure as plastic materials and that the present structure is due to such plastic movement or flowage.

Texture of the ore.—Ramdohr [28] divides the textures found in the Rammelsberg ores into two groups: One in which he places pyrite and marcasite, which commonly show the "Gelstrukturen," or gel structure; and a second group, in which he places galena, sphalerite and chalcopyrite, which as a rule display a fine-grained symmetrical "polygonal" texture. Ramdohr states that the minerals of his second group also display the "Gelstrukturen" in places where this has not been oblitered by the secondary fine-grained texture. The fine-grained "polygonal" texture he considered to be a secondary one developed by recrystallization of the minerals.

In the present examination of the structure and texture of the

[28] *Op. cit.*, pp. 1013–1068. Considerable discussion is given in this paper on the deformation and recrystallization of the ore minerals at Rammelsberg.

Rammelsberg ores, the "gel structure" shown in photographs accompanying Ramdohr's paper was not observed in any of the specimens available for our examination.

Texture of Sphalerite.—The texture of the sphalerite in the banded ore was not well determined. This was due to the difficulty of etching the sphalerite in the presence of so much included chalcopyrite. Enough of the texture was revealed, however, to show that the sphalerite had a fine-grained equidimensional texture with polysynthetically twinned crystals.

Texture of Galena.—The Rammelsberg galena displays a rather fine-grained schistose texture upon etching. The crystals are slightly elongated and with an orientation (in one plane) which is definite enough to determine the direction of banding in the specimen when looking at the microscopic field alone. A very definite flow texture is seen in rows of orientated, elongated crystals curving conformably about the outline of sphalerite and pyrite masses in the galena.

A texture of apparently equidimensional crystals, in places appears to replace the slightly elongated crystal texture and is interpreted as a recrystallization of the galena. In some places the equidimensional texture alone was observed.

Texture of Chalcopyrite.—The texture of the chalcopyrite of the Rammelsberg ores was found to be quite different from the texture of the chalcopyrite of the ores examined from other localities (Figs. 7 and 8). The grain size is much smaller, individual crystals varying from 0.005 to 0.040 mm. in diameter, and the texture is a pattern of anhedral crystals analogous to the textural pattern of a quartzite. No twinning was noted in these crystals.

Throughout many of the sections examined, this same fine-grained quartzitic texture of chalcopyrite was evident. Several, however, possess a texture which revealed what the writers interpret as the originally deformed state of the chalcopyrite (Fig. 8). Enclosed by typical fine-grained crystals several residual patches of large crystals were found upon etching. The larger crystals making up these residual patches were strikingly elongated, single crystals having their length or elongated direc-

tion equal to as much as fifteen times their width. In their elongation, these crystals resemble the ribbon-like elongated galena crystals of the Coeur d'Alene ores. Approximate dimensions of some of the larger elongated crystals may be taken as 0.10 mm. wide and 1.5 mm. in length. There is thus seen to be a great difference in grain size between the older deformed crystal texture of the chalcopyrite and the newer fine-grained equidimensional crystal texture which has effaced it.

Many of the large elongated crystals are strongly twinned, the polysynthetic twinning forming a closely spaced, hatched pattern and the twin lamellæ making a constant angle of 30° to 50° with the long direction of the crystal. Plastic deformation of these chalcopyrite crystals effected a remarkable elongation, undoubtedly by slippage along gliding planes and accompanied by polysynthetic twinning, with apparently an accompanying preferred orientation of the crystals as shown by their slight difference in etch reaction, and the relations of the twin lamellæ.

The extent of deformation required to produce lamination of the chalcopyrite and sphalerite, and other flow structures as described above, should certainly produce just such greatly elongated chalcopyrite crystals as are here described. Undoubtedly, the Rammelsberg ores have suffered severe deformation. The stress producing the deformation caused a flowage of the chalcopyrite which proceeded by slippage along gliding planes and by polysynthetic twinning within the crystals, resulting in their elongation. The texture of elongated, plastically deformed chalcopyrite crystals now seen only in remnant patches in some sections of the ore, was doubtless at one time possessed by much of the chalcopyrite of the ores now displaying the flowage structure. The crystal elongation, however, has, according to the writers' interpretation, been effaced by the later developed fine-grained quartzitic crystal texture. This later fine-grained texture, the writers believe, is due to recrystallization of the highly strained deformed chalcopyrite. The recrystallization may have followed closely the deformation or may have gone on concurrently with it, or it may have been separated by a time interval; it probably followed the deformation. The process of deformation

and recrystallization of the chalcopyrite here effected by nature is believed to be quite analogous to the recrystallization of deformed crystals as described in the metallurgical literature[29] (Fig. 6). Although this conclusion has the dangers inherent in reasoning by analogy, it is supported by the fact that it harmonizes with the geological evidence.

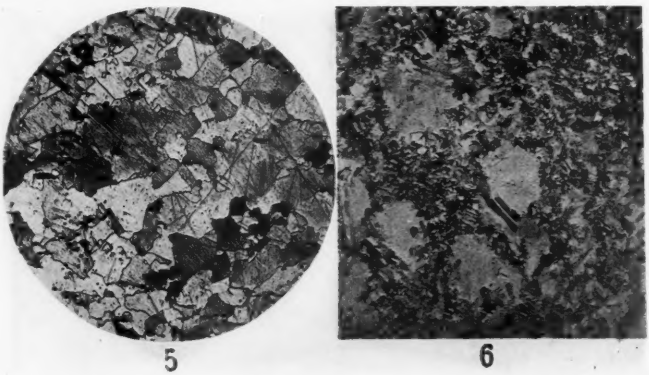

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FIG. 5. Typical undeformed chalcopyrite. Crystals show no elongation or twinning. United Verde Mine, Jerome, Arizona. ×65.

FIG. 6. Cold worked, well deformed alpha brass partly recrystallized by annealing. The large deformed crystals on further annealing would break down into the fine-grained recrystallization texture. ×75. Courtesy of the Physical Metallurgy Laboratory, Mass. Inst. of Tech.

CONCLUSIONS.

1. Criteria of flowage and plastic deformation of an ore mass, based on the apparent flow structures as seen in hand specimens, are usually unreliable because the apparent flow lines around inclusions may have been inherited from replaced rock.

2. An ore mass composed in whole or in part of the minerals galena, sphalerite, and chalcopyrite, which has been strongly de-

[29] Matheson, C. H., and Phillips, Arthur, "Recrystallization of Cold-Worked Alpha Brass on Annealing," *Trans. Am. Inst. Min. Eng.*, *54*, 1916, pp. 608–670.

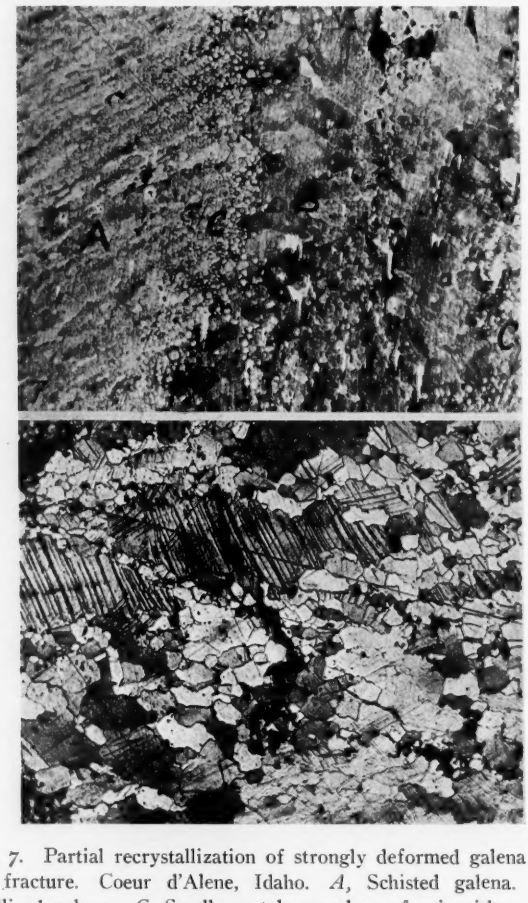

FIG. 7. Partial recrystallization of strongly deformed galena along a small fracture. Coeur d'Alene, Idaho. *A*, Schisted galena. *B*, Recrystallized galena. *C*, Small crystals on edges of vein either residuals of *A* or first stage of *B*. × 60.

FIG. 8. Deformed and partly recrystallized chalcopyrite, Rammelsberg, Germany. The large elongated highly twinned chalcopyrite crystals are interpreted as being deformed residuals left by the recrystallization which formed the small crystals surrounding them. Compare with Fig. 6. × 60.

formed, will show in its texture that flowage has taken place unless complete recrystallization has occurred. The extent of recrystallization and size of crystals produced by it are a function of strain and composition in the crystal and of time and temperature. The presence of water would doubtless assist the process. It would be mere chance if not an impossibility that the whole typical texture of a replacement orebody of several minerals should be deformed, and the stressed crystals recrystallize to their original relations and relative sizes. Unless *complete* recrystallization of the entire ore mass takes place, two generations of each mineral should be found.

The general case of recrystallization with only one mineral involved if carried to completion so that only one generation of crystal is present, and if carried to the stage of crystal size, like that common to the typical replacement grain size for that mineral would be difficult if not impossible to detect by microscopic means. In practice this difficulty in interpretation should be seldom encountered since mono-mineral ores are rare.

3. Quartz, a mineral that is commonly present in the enclosing schist as an original rock mineral, showing parallel elongation and frequently a preferred orientation, is found as an introduced mineral in schist replacement deposits showing no preferred direction of elongation or orientation. Such a conclusion is trite perhaps, but its significance appears to have been often neglected.

4. The ores at Blue Hill, Maine, are of post-regional metamorphism age, a conclusion based on their relation to the later granite intrusive, and supported by their cross-cutting relations to schist and the microscopic study of the ore and gangue minerals.

5. The orebody at Milan, N. H., shows by its ore and gangue minerals that it has suffered only a small amount of deformation. The wall rock contains cordierite as an alteration product.

6. Ore from the Mandy orebody, Manitoba, shows the microscopic texture of a normal replacement ore. The apparent flow structure in the ore does not conform to the walls of the orebody, but rather to the flow structure of the adjoining rock, from which it is doubtless inherited by replacement.

7. Strong deformation with apparently some later recrystallization has taken place in the Rammelsberg ore from Goslar, Germany. This deformation has elongated the crystals parallel to the banding of the ore and presumably has been at least a partial cause of the banding. Two markedly different sizes of chalcopyrite grain are present, one large, greatly elongated and strained, the other fine-grained, equidimensional to slightly elongated, and showing no strain effects.

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ORIGIN OF THE WHITE CLAYS OF TUSCALOOSA AGE (UPPER CRETACEOUS) IN ALABAMA, GEORGIA AND SOUTH CAROLINA.

GEORGE I. ADAMS.

Distribution of the Clays.—The clays which are here considered occur in the basal Upper Cretaceous formation that lies at the inner border of the Coastal Plain adjacent to the Appalachian region in the southeastern United States. The eastern part of the formation, extending from North Carolina through South Carolina into eastern Alabama, was once referred to the Lower Cretaceous, but is now acknowledged to be of Upper Cretaceous age. In a recent correlation paper, Cooke [1] has shown that the Cape Fear formation of South Carolina and its continuation, the Middendorf formation of Georgia, are essentially the equivalent of the Tuscaloosa formation in Alabama, which is recognized as extending through Alabama, the northwestern corner of Mississippi, western Tennessee and western Kentucky. Since the name Tuscaloosa has priority,[2] it is appropriate to extend its use to the whole of the belt of the basal Upper Cretaceous as shown on the accompanying sketch map, Fig. 1.

The Tuscaloosa formation although variable in character is of continental origin. The only fossils it has yielded are plant leaves. In Alabama it is known to extend under cover for a distance of seventy-five miles or more to the south of the belt in which it outcrops. Its inner border has been removed from a wide area. It was evidently spread over an extended piedmont plain, which was developed during the early Mesozoic, from the Atlantic coast to the head of the Mississippi embayment.

The deposits of white clays of Tuscaloosa age, at localities in Georgia, South Carolina and Alabama have been described in con-

[1] Cooke, Wythe, U. S. Geol. Surv. Prof. Paper 140, p. 138, 1926.

[2] Smith, E. A. and Johnson, L. C., U. S. Geol. Surv. Bull. 43, pp. 95–116, 1887.

siderable detail. Those of Georgia are first in importance, those of South Carolina are second, and those of Alabama are third. The latter, however, are of particular interest since their consid-

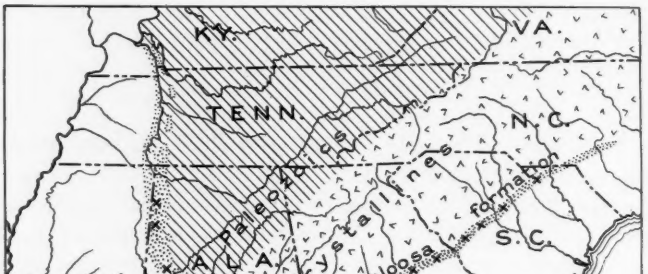

FIG. 1. Sketch map showing the relations of the Tuscaloosa formation to the crystallines and Paleozoics and the general distribution of the rocks to clays in the formation.

eration raises a new view point in regard to the problem of the origin of the deposits. The occurrences in the other states are not so well known, and are, therefore, less instructive.

Previous Theories of Origin.—The origin of the Georgia deposits of white clays was first discussed by Veatch.[3] According to him the crystalline rocks of the Piedmont Plateau, which are largely feldspathic, yielded on weathering, clayey material, the finer particles of which were deposited in the quiet waters of deltaic lakes as lenticular beds of pure white clay.

[3] Veatch, O., "Kaolins of the Dry Branch Region, Georgia," ECON. GEOL., vol. 3, pp. 109–117, 1908. Second Report on the Clay Deposits of Georgia, Georgia Geol. Surv., Bull. 18, pp. 97–103, 1909.

Newmann [4] has offered the criticism that deposition in fresh water deltaic lakes, should show signs of banding and therefore since the clays are massive, the explanation by Veatch is not satisfactory. In discussing the origin of the white clays of South Carolina, Newmann explained [5] that a white residuum, produced by the weathering of the alkalic-feldspathic Piedmont area under a dense covering of vegetation, was carried to the sea, and that the clayey matter coagulated by the salt of the sea water was deposited in the quiet areas between deltas where continuous deposition gave rise to massive lenticular beds.

He agrees with Veatch as to the derivation of the clays from the Piedmont crystallines, but explains that most of the iron was leached from the Piedmont rocks by organic acids and carbon dioxide while the area was in a physiographically old age stage and covered with a heavy growth of vegetation which was made possible by abundant precipitation. Thus a heavy white residuum was formed which on subsequent uplift was eroded and transported to form the white clays. Later uplift and changed climatic conditions gave rise to a residual material that was deposited as ferruginous beds overlying the white clays and sands.

Woolnough [6] on reading the paper by Newmann contributed a discussion, based on his observations in Australia, in which he states that it is not necessary to invoke in the transportation and deposition a selective sorting out of iron minerals from a red regolith formed under a pluvial climate, since immediately following complete peneplanation the regolith was probably leached of all its iron. He also stated that if the rainfall was markedly seasonal the residuum on the peneplain would consist of a "duricrust" of ferruginous matter and a substratum of clay which when transported would be sorted; the ferruginous material being deposited in the form of alluvial fans, whereas the pure clay carried farther would be deposited in any deep basin competent to receive it.

[4] Newmann, Fred R., "Origin of Cretaceous White Clays of South Carolina," Econ. Geol., vol. 22, 4, pp. 374–387, 1927.

[5] *Op. cit.*

[6] Woolnough, W. G., "Origin of White Clays and Bauxite and Chemical Criteria of Peneplanation," Econ. Geol., vol. 23, 8, pp. 887–894, 1928.

Smith,[7] who has recently made a detailed examination of the clays of Georgia, reviewed the theories of origin of the white clays and concluded that Veatch's explanation, as modified by Newmann, is essentially correct. He also states that the origin of the sedimentary kaolins of Eocene age in Georgia was probably similar to those of the Cretaceous, although the source of the kaolin may have been in part from erosion of some of the deposits in the Cretaceous beds.

Proposed Theory of Origin.—Turning now to the white clays of the Tuscaloosa formation in Alabama[8] it may be pointed out in the beginning that those in the western part of the state (Fig. 1), overlie the Paleozoic rocks of Coal Measure age, and that they are too distant from the crystallines to have been derived directly from them. Any theory of origin which accounts for these clays must have a different starting point. It is of course true that the average sedimentary rock approaches closely the chemical composition of the average igneous or metamorphic rock and consequently, although it has been the fashion to think of kaolins as derived rather directly from feldspathic rocks, the sedimentary rocks are also an adequate source. The writer grants that the Tuscaloosa sediments opposite the crystallines and the material of the white clays in them were probably derived from the crystalline, but he believes that the white clays in that district were not the result of marine deposition as explained by Newmann.

He offers the suggestion that since the lenses of white clay in the Tuscaloosa formation vary up to 50 feet or so in thickness, and a maximum of only about one thousand feet in lateral extent, and usually are much smaller, they are not commensurate with conditions of marine deposition such as Newmann postulated. Moreover, Newmann cites the occurrence in South Carolina of black lignitic clays at the base of some deposits and states that this material grades upward through gray and buff to a white

[7] Smith, Richard W., "Sedimentary Kaolins of the Coastal Plain of Georgia," Geol. Surv. of Georgia Bull. 44, 1929.

[8] For detailed descriptions see: Ries, Heinrich, Preliminary Report on the Clays of Alabama, Geol. Surv. of Alabama, Bull. 6, p. 81, *et. seq.*, 1900.

clay. The lignitic material does not imply marine deposition between deltas.

The Tuscaloosa formation appears to have been deposited by overloaded streams crossing a coastal plain between the highlands in the southern Appalachian region and a coast line far beyond the belt in which the basal Upper Cretaceous beds now outcrop. Perfect peneplanation, it may be remarked, is rarely attained and probably was not in this instance. Moreover, the formation of a white residuum seems inapplicable to the conditions under which the Tuscaloosa formation was deposited. The appeal to the coagulating influence of salt water as a cause of continuous deposition which resulted in the massive character of the white clays is ingenious, but it seems improbable that it should have been operative so seldom, in very limited areas and without the burial of any marine life.

The deposition of clayey material in small shallow freshwater lakes is more commensurate with the extent of the white clay bodies, but it does not explain the massive character of the beds. It is here suggested that the massive character and the purity of the clay are the result of the local alteration of deposits of impure clays.

Analogy with Bauxite Deposits.—Anyone who has studied the bauxite deposits in the southern Appalachian region at localities where they occur in the Paleozoic rocks, will recall their limited extent, lens-like or pot-shaped form and association with massive white clays; for some of the deposits are only in part bauxitic. They seem to have originated in place as the result of processes which have operated locally and probably climatic conditions have been an important factor in the alterations which resulted in the clays and bauxites.

The writer has argued [9] that the bauxites of the southern states were all formed during Wilcox (Eocene) time. There is bauxite in northeastern Mississippi, eastern Alabama and western Georgia, which is in the Wilcox group. In central Georgia, in the Tusca-

[9] "Bauxite Deposits of the Southern States," ECON. GEOL. vol. 22, pp. 615–620, 1927.

loosa formation, there is bauxite associated with the white clays which may have been formed by alteration of the clay lenses during Wilcox time.[10] The bauxite deposits in the area of the Paleozoics of the Appalachian region are found where dolomites or limestones have been subjected to deep weathering, and are probably due to local alteration during the time when the other bauxite deposits were formed. For these deposits, found in pockets, an origin in sink-holes has been suggested by the writer.[11] Reference to the bauxites and the white clays associated with them is made here for the purpose of showing that there is a type of local alteration exhibited by them which may result in pure massive beds such as are found in the Tuscaloosa formation. Bauxite alteration appears, however, to be a special phase of the general process, which operates in the zone of weathering.

No attempt is made at this time to explain the chemical processes which are involved in the production of the white clays. The problem is one which merits consideration and it is hoped that it will be solved. The purpose of this article is to reopen the discussion of the origin of these clay-deposits, which are of scientific interest and economic importance. A satisfactory explanation must be applicable to all the white clays in the region which are similar in character, whether their sources were the crystallines and metamorphics, or the sedimentary areas, and whether they occur in the Tuscaloosa or other formations.

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[10] Smith reported me as assuming that the bauxite in central Georgia is in the Wilcox formation. The statement above makes my meaning clear. We are in essential agreement since he says that it is entirely possible that some of the kaolin deposits of the Midway and of the Cretaceous were exposed to conditions that resulted in their partial alteration to bauxitic clays and bauxites.

[11] ECON. GEOL., vol. 18, pp. 410–412, June–July, 1923.

A QUANTITATIVE AND QUALITATIVE DETERMINATION OF THE ORES OF COBALT, ONTARIO.

PART II.

ELLIS THOMSON.

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Part II.

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RELATIONS OF THE METALLIC MINERALS TO THE DIABASE SILL.

IT seemed to the writer a reasonable hypothesis that the type of metallic mineralization might vary in some manner or degree with the distance from the diabase sill or with the country rock in which the vein occurs. With this in mind, the microscopic analyses were carefully reviewed to see whether there was any evidence of such control exerted either by the distance from the diabase sill or by the character of the country rock. In addition it was hoped that, in this critical review, some relation between the other metallic minerals and the native silver might be evolved. A diagrammatic section (Fig. 21) was then prepared showing the mineral content, position with regard to nearest point of the diabase sill, and the approximate quantitative mineralogical composition. Each mineral is designated by its starting letter and one other, usually the second. Capitals are used for the initial letter in the case of major constituents, and small initial letters indicate minor constituents. Bornite, chalcocite and covellite are

included with chalcopyrite, sphalerite with galena, argentite with silver, and marcasite and pyrrhotite with pyrite. These sections are shown in Fig. 21.

Several important facts are brought out in this diagram. First, it will be noted that niccolite is commonest in specimens from the Mining Corporation workings, is sparingly present in

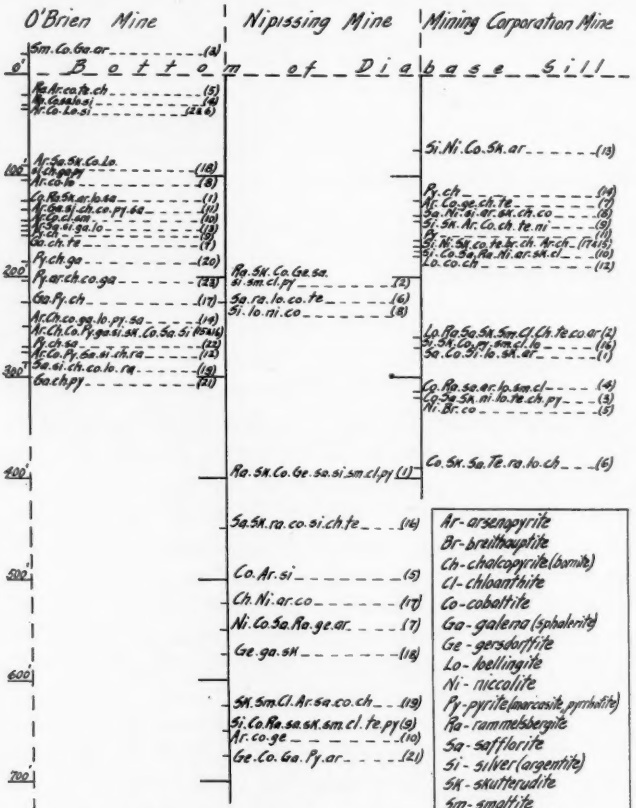

FIG. 21.

those of the Nipissing Mine, and is entirely lacking in those from the O'Brien Mine. On the other hand, galena and sphalerite are lacking in the Mining Corporation suite, are but sparingly represented in those specimens from the Nipissing Mine, and are most abundant in the O'Brien Mine ores. Of the iron sulphides pyrrhotite is fairly common in the O'Brien Mine, and pyrite and marcasite are almost lacking. In contrast to this, pyrite and marcasite occur sparingly in the Nipissing and Mining Corporation suites, and pyrrhotite is absent. Tetrahedrite occurs in small amounts in ores from all three mines but is less common in those from the O'Brien Mine than in those from the other two. Arsenopyrite, next to cobaltite and safflorite the commonest metallic arsenic mineral of the district, is most abundant in the O'Brien ores. So that the dual relation of the quantitative proportions of these minerals with regard to native silver and their distance from the diabase sill might be more clearly visualized, graphs were prepared, that show both these features in a diagrammatic way. As before, major constituents are given a unit value and minor constituents a half. Most of the specimens from these three mines came from a distance of about 700 ft. from the diabase sill. The only exceptions are to be found in three from the Nipissing Mine which were 1,100 ft. distant from this igneous body. Since there is a gap of 400 ft. between these three and the remainder of the specimens, these isolated specimens were not taken into consideration in making up these diagrams, which are shown in Figs. 22, 23, 24 and 25.

Since marcasite and pyrrhotite are for the most part later in time of deposition than the silver, and pyrite is present in minor quantities, the iron sulphide diagram is omitted. As the other sulphides appear for the most part to be later in time of deposition than the silver, no diagrams were prepared for them.

In interpreting these diagrams, it must be borne in mind that all gangue minerals were omitted and the rough percentages given are of the metallic minerals alone. In many cases the carbonate or carbonate and quartz gangue make up more than 50 per cent. of the section. Since there are many barren veins,

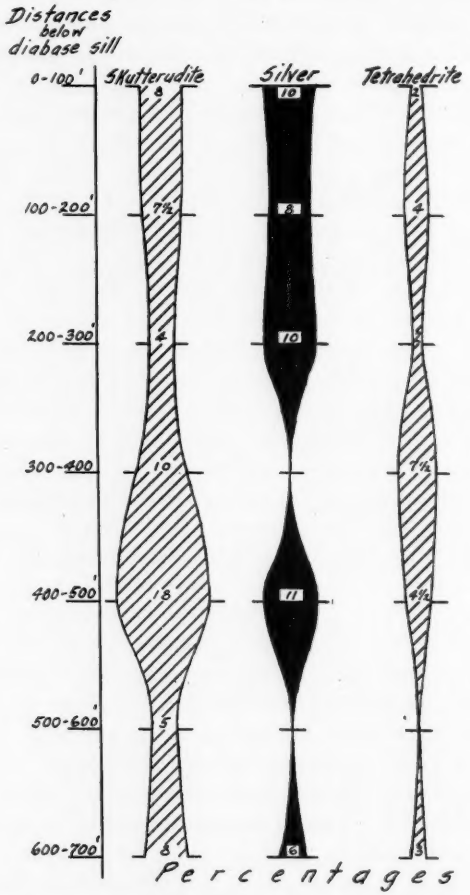

FIG. 22. Composite diagram showing varying proportions (approximate) of skutterudite, tetrahedrite, and native silver to total metallic mineral content with increasing distance from diabase sill.

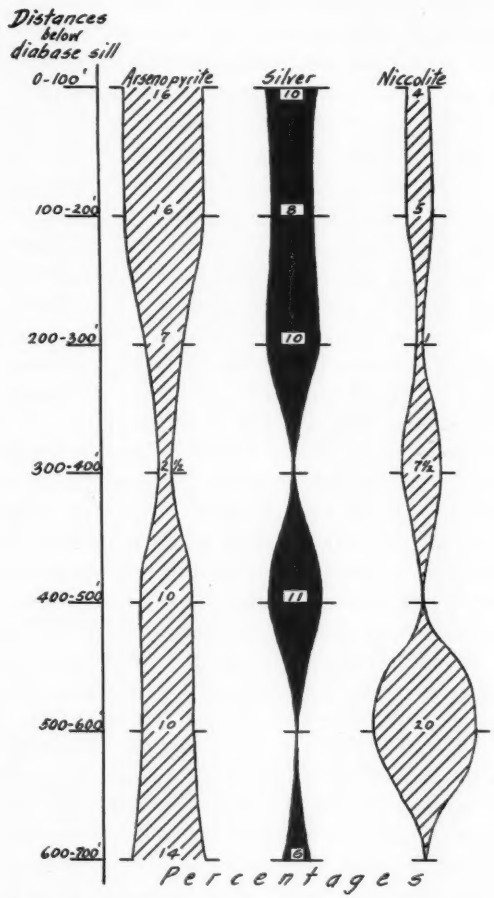

FIG. 23. Composite diagram showing varying proportions (approximate) of arsenopyrite, niccolite, and native silver to total metallic mineral content with increasing distance from diabase sill.

filled with these gangue minerals, that carry little or no metallic mineralization, it seems unlikely that these non-metallic minerals could have played any very important rôle in the silver deposition. In any event their part in this deposition will not be considered in this paper. It must be remembered also that a *composite picture of many veins* is here presented. As more specimens were examined within the range 0–400 ft. from the diabase, more weight may be attached to this part of the diagram than to that dealing with the last 300 ft. It will be noted, however, that, even for this latter section, the distance between specimens averages about 30 ft., so that a fair cross-section of it also was obtained. An inspection of these diagrams serves to bring out one or two salient features, which may be briefly mentioned at this point. First, there is a general parallelism, with local fluctuations, between the diagrams for silver and those for the minerals, arsenopyrite, cobaltite, loellingite, rammelsbergite, and skutterudite. On the other hand the diagrams for niccolite, safflorite and tetrahedrite seem to show the reverse relation with silver. From this it would appear that arsenopyrite, loellingite, skutterudite, rammelsbergite, and cobaltite are the most potent of these minerals in depositing the silver, whereas the others, at least in certain parts of the section, were inimical to it. It must, however, be remembered that native silver does occur in association with all these minerals in greater or less amount. The results obtained, therefore, give only the relative importance of these minerals with regard to silver deposition. Moreover, it can hardly be considered that these findings are final for the last three hundred feet since the sections examined in this part of the section were few in number and taken from one mine only. They may, however, be useful as pointing the way for future investigation in the quantitative field. It is interesting to note in this connection that both at the O'Brien Mine proper and at the Cross Lake claim of the same mine, some ½ mile to the southeast, silver is found in considerable abundance in association with a metallic mineralization that is largely arsenopyrite. Considerable quantities of silver have also been found in association with

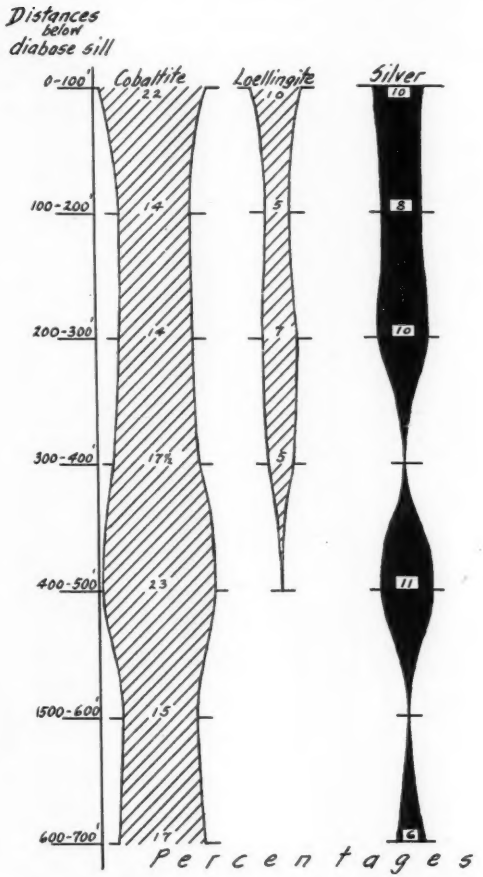

FIG. 24. Composite diagram showing varying proportions (approximate) of cobaltite, loellingite, and native silver to total metallic mineral content with increasing distance from diabase sill.

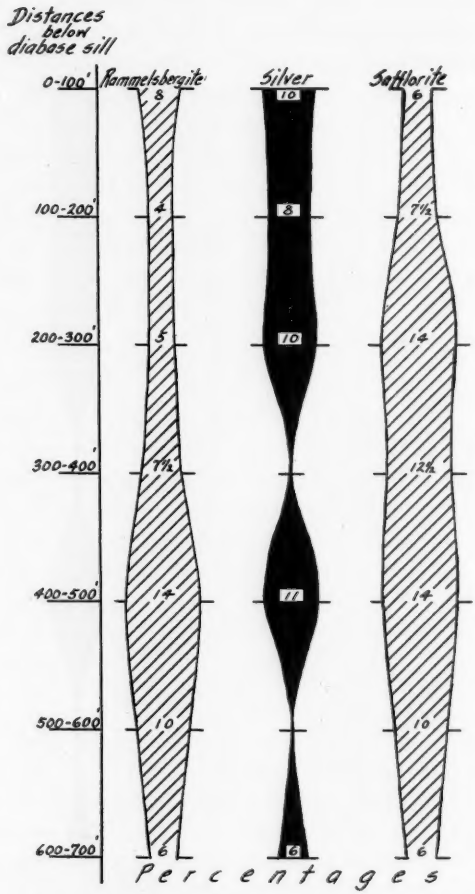

FIG. 25. Composite diagram showing varying proportions (approximate) of rammelsbergite, safflorite, and native silver to total metallic mineral content with increasing distance from diabase sill.

almost pure loellingite, both in this field and in the South Lorraine district some 20 miles to the east. This agrees in general with the results obtained in the arsenopyrite and loellingite diagrams. It had been hoped to carry out this quantitative investigation in a more exact way, following the procedure as outlined

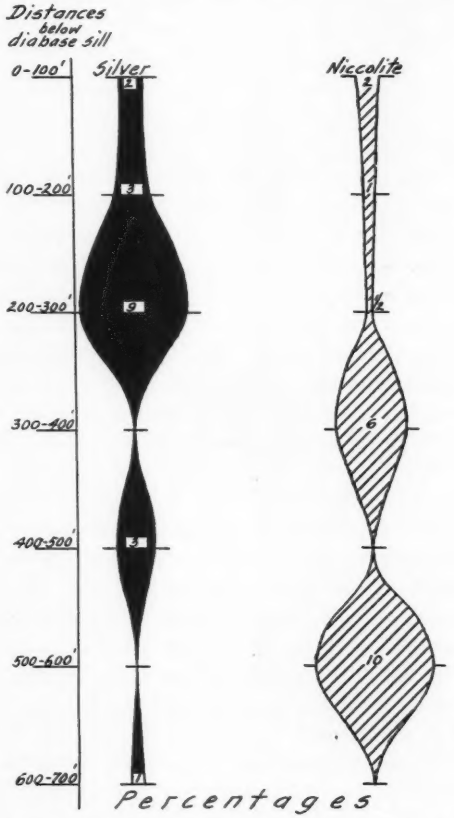

FIG. 26. Composite diagram showing varying proportions (a real determination) of niccolite and native silver to total metallic mineral content with increasing distance from diabase sill.

in a previous paper [20] but it was found impossible to do this for all the minerals in these sections on account of the intimate association of these minerals in many cases and the impossibility of differentiating several of the minerals individually from the remainder. As a check on these results, such exact quantitative determinations were made on the minerals niccolite and native silver. The determinations were carried out on the ground-glass screen of the metallographic machine, using the areal method of determination. The results of these determinations are shown in the next set of diagrams, Fig. 26.

In general, these agree with the diagrams as obtained by the approximate quantitative methods cited previously, differing for the most part in degree only, particularly in the case of native silver. It would, therefore, seem reasonable to suppose that the main facts, as brought out by the first set of diagrams, would not be affected materially by more accurate quantitative determinations of this character. The agreement between these two sets of results is really surprising when the approximate character of the first method is considered.

To summarize briefly, the main features brought out by this quantitative analysis of the ores with relation to the diabase sill, all of the metallic arsenides and sulpharsenides have played a certain part in the deposition of silver but some would seem to have been more important in this connection than others. As has been mentioned before, it seems probable at least that arsenopyrite, cobaltite, loellingite, skutterudite, and rammelsbergite were beneficial, but niccolite, tetrahedrite and safflorite, at least in large amounts, seem to have been inimical to the precious metal deposition. The character of the rocks in which the veins occur is another possible factor, though probably one of less importance than the metallic mineralization with which the silver ores are so intimately associated. The veins are to be found in rocks of both volcanic and sedimentary origin, the former being represented by those at the O'Brien Mine whereas the ores of the

[20] Thomson, E., "Quantitative Microscopic Analysis," *Jour. of Geol.*, vol. 38, pp. 193–222.

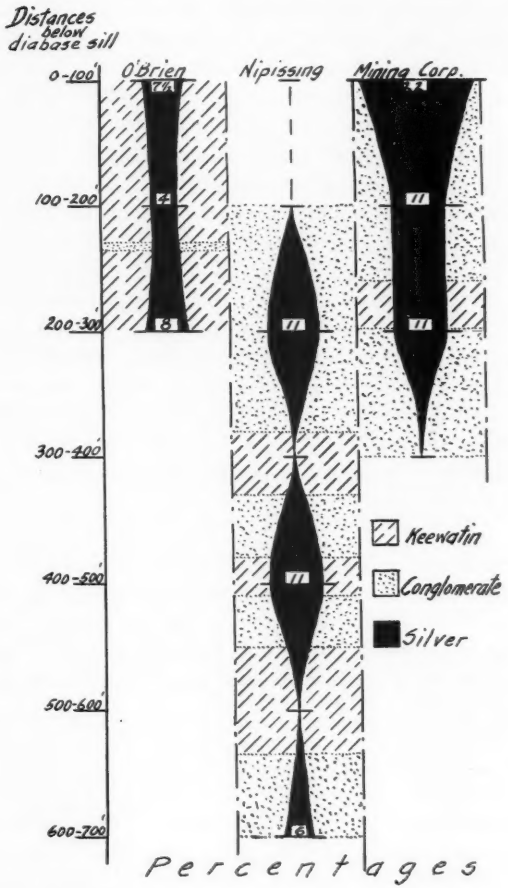

FIG. 27. Composite diagram showing varying proportions (approximate) of native silver to total metallic mineral content at the O'Brien, Nipissing, and Mining Corporation mines, with increasing distance from diabase sill, also the enclosing country rocks.

Mining Corporation and Nipissing Mines occur chiefly in the conglomerates and slates of the Cobalt Series. A tabulation of the metallic minerals in relation to the rocks in which the veins occur, gave no clue whatever to the relative importance of this factor. This is more clearly demonstrated by the graph in Fig. 27, where the proportions of silver at the different distances and the geological formations are both plotted in diagrammatic fashion for the specimens taken at the three mines. From this evidence, the character of the enclosing rock would seem to have little or no bearing on the *proportion of silver to other metallic minerals present* in the *vein system as a whole*, though in individual veins this factor may be an important one.

In addition to the three suites of specimens collected from the workings of these three mines, other specimens, not so exactly located, were examined microscopically, and their constituent minerals determined. The same microchemical reagents were used as before. These are listed below.

Description of Additional Specimens.

The specimens in this suite were taken at random from the collection of the Royal Ontario Museum of Mineralogy and represent 16 of the older mines of the district, besides including specimens from the O'Brien and Nipissing Mines. They are arranged according to the mine locality, in alphabetical order.

No.	Locality.	Major Met. Min.	Minor Met. Min.
Be 1....	Beaver Mine	Arsenopyrite, safflorite, cobaltite	Rammelsbergite, chalcopyrite
Bu 1 ...	Buffalo Mine	Niccolite, cobaltite	Skutterudite, smaltite, chloanthite
Cl 1....	Columbus Mine	Cobaltite, gersdorffite	
Cn 1 ...	Coniagas Mine	Silver, loellingite	Cobaltite, skutterudite, argentite, timiskamite
Co 1 ...	Cobalt Lake Mine	Cobaltite, niccolite, rammelsbergite, skutterudite	Smaltite, chloanthite, safflorite
F 1.....	Foster Mine	Niccolite	Safflorite, cobaltite, rammelsbergite

The major metallic mineral, niccolite, is associated with long slender needles of safflorite (Fig. 19).

No.	Locality.	Major Met. Min.	Minor Met. Min.
F 2.....	Foster Mine	Rammelsbergite, safflorite, skutterudite	Cobaltite, arsenopyrite, silver, tetrahedrite
Ha 1...	Hargrave Mine	Safflorite, rammelsbergite, loellingite	Cobaltite, tetrahedrite, bornite, chalcopyrite, arsenopyrite

Tetrahedrite, bornite and chalcopyrite in that order of prevalence, cut the other minerals in the form of small irregular veins (Figs. 28 and 29).

No.	Locality.	Major Met. Min.	Minor Met. Min.
Hu 1...	Hudson Bay Mine	Rammelsbergite cobaltite	gersdorffite
L 1.....	La Rose Mine	Safflorite, loellingite	Rammelsbergite cobaltite, chalcopyrite, tetrahedrite
L 2.....	La Rose Mine	Xanthoconite	Argentite

The major mineral in this section has already been described by Parsons [21] as occurring in this district. In polished section it is grayish white in color, shows an internal reflection yellow to light brown, is etched yellow to brown with KCN, rubbing to rough brown differential surface. It is negative to the other five reagents of Davy-Farnham. It occurs in crested groups of crystals with a narrow rim of argentite.

No.	Locality.	Major Met. Min.	Minor Met. Min.
L 3.....	La Rose Mine	Safflorite, loellingite	Rammelsbergite, cobaltite, skutterudite, chalcopyrite, tetrahedrite
Me 1...	Meteor Mine	Bismuthinite, bismuth	Silver, argentite, chalcopyrite, sphalerite

In this section these two bismuth minerals occur in disseminated form (Fig. 30) associated with a quartz gangue, in places in vein-like forms but more commonly in irregular masses. Sphalerite sometimes forms a narrow rim round the bismuth areas, and chalcopyrite, silver and argentite are rare constituents.

[21] Parsons, A. L., Univ. of Toronto Studies, Geol. Series, No. 17, pp. 11–12, 1924.

No.	Locality.	Major Met. Min.	Minor Met. Min.
N 22...	Nipissing Mine	Niccolite	Breithauptite, cobaltite

Niccolite makes up the major portion of this section but irregular areas of breithauptite (Fig. 31) and numerous small crystals of cobaltite are scattered plentifully throughout the mass of the niccolite.

No.	Locality.	Major Met. Min.	Minor Met. Min.
O 24...	O'Brien Mine	Tetrahedrite	Chalcopyrite
O 25$_1$...	O'Brien Cross, Lake Claims	Arsenopyrite	Galena, chalcopyrite, silver, sphalerite, pyrrhotite
O 25$_2$...	O'Brien Cross Lake Claims	Silver, skutterudite cobaltite	Safflorite, loellingite rammelsbergite
O 25$_3$...	O'Brien Cross Lake Claims	Arsenopyrite	Cobaltite, gersdorffite, silver, chalcopyrite sphalerite, pyrrhotite
O 26....	O'Brien Mine	Silver	Chalcopyrite, argentite
O 27....	O'Brien Mine	Stephanite	Chalcopyrite
P 1.....	Penn-Canadian Mine	Rammelsbergite cobaltite, niccolite	safflorite, gersdorffite, skutterudite
SB 1...	Silver Bar Mine	Skutterudite, smaltite, chloanthite, rammelsbergite	cobaltite, gersdorffite safflorite
SC 1...	Silver Cliff Mine	Chalcopyrite, bornite, silver	Chalcocite, magnetite
SQ 1...	Silver Queen Mine	Niccolite, breithauptite, silver	cobaltite skutterudite
T 1.....	Timiskaming Mine	Rammelsbergite	Cobaltite, gersdorffite, niccolite
T 2.....	Timiskaming Mine	Rammelsbergite	Cobaltite, niccolite, skutterudite arsenopyrite, tetrahedrite, chalcopyrite, silver
T 3.....	Timiskaming Mine	Safflorite, cobaltite, skutterudite	Rammelsbergite, loellingite, gersdorffite, smaltite, chloanthite, niccolite
U 1....	University Mine	Arsenopyrite	Argentite, silver
U 2....	University Mine	Niccolite, safflorite, cobaltite	Rammelsbergite

An examination of Table III., which includes both sets of specimens, indicates that the old order, as shown in Table II., is largely maintained, with but slight differences in the relative positions of safflorite and arsenopyrite at the top of the table, and of smaltite, gersdorffite, and chloanthite, at the bottom. It is

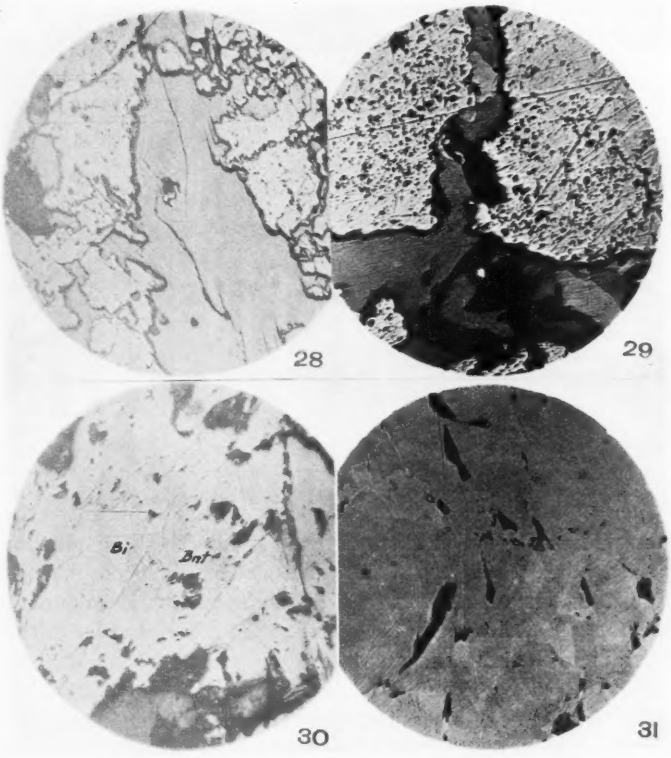

FIG. 28. Spec. Ha 1. White, safflorite; lt. gray, tetrahedrite; black, gangue. × 105.

FIG. 29. Spec. Ha 1. White, safflorite; dark gray, bornite; light gray, chalcopyrite; black, gangue. × 105.

FIG. 30. Spec. Me 1. Bi, native bismuth; Bnt, bismuthinite; black, gangue. × 105.

FIG. 31. Spec. N–22. Lt. gray, niccolite; dark gray, breithauptite; Black, gangue. × 105.

TABLE III.

RELATIVE ABUNDANCE IN NUMBER OF OCCURRENCES.

	Min. Corp.	Nip.	O'B.	Others	Total
1. Cobaltite	13½	10½	13½	13	50½
2. Safflorite	8½	10	8	9	35½
3. Arsenopyrite	6½	5	16	5½	33
4. Silver	8	7½	8	8	31½
5. Skutterudite	8½	8½	3	7	27
6. Rammelsbergite	5	7	4	10½	26½
7. Chalcopyrite	5	4	8½	6½	24
8. Loellingite	4½	3½	5½	5½	19
9. Niccolite	6	5½	—	7	18½
10. Galena	—	1½	10½	½	12½
11. Tetrahedrite	4	2½	1½	3½	11½
12. Smaltite	2½	5	1½	1½	10½
13. Gersdorffite	1½	5	—	3½	10
14. Chloanthite	2½	5	½	1½	9½
15. Pyrite	3	2½	3½	—	9
16. Pyrrhotite	—	—	7½	1	8½
17. Sphalerite	—	—	5	1½	6½
18. Breithauptite	1½	1	—	1½	4

noteworthy also that the three last-mentioned minerals are in the last third of the list and have only the sulphides of iron and zinc and breithauptite below them. The relatively high position occupied in this table by galena is due largely to its abundance at the O'Brien Mine. It is rare or lacking in other localities. The position of tetrahedrite above smaltite, chloanthite, and gersdorffite is rather surprising, as also its fairly uniform distribution in all parts of the district. Pyrrhotite and sphalerite are confined largely to the O'Brien Mine specimens. Niccolite seems to be fairly widespread except at the O'Brien Mine, where it is rare. No occurrences of this mineral are recorded in the sections from the O'Brien Mine examined for this paper. Although the specimens collected were chosen rather for their content of the other metallic minerals, native silver is fairly abundant in them, as indicated by the position of this mineral in the list. It seems probable that a greater number of specimens might place it slightly higher in the scale. So that the relative abundance of these minerals might be shown graphically, a diagram (Fig. 32) is included, the minerals being listed in the same order as before, *i.e.*,

according to prevalence. Since the section from the Beaver Mine was examined after this diagram was prepared, the results from this section are not included.

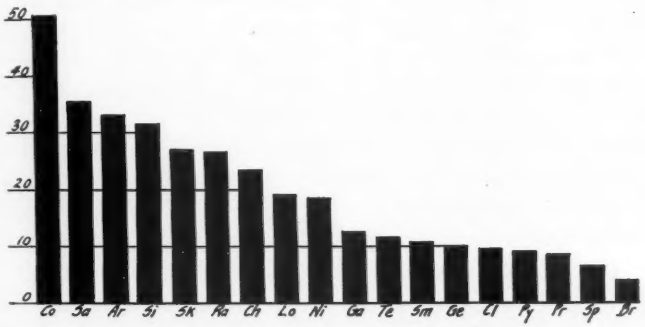

FIG. 32.

RARE MINERAL OCCURRENCES IN THE COBALT DISTRICT.

In addition to these commoner minerals of the district, occasional occurrences of rarer minerals, have been reported from time to time. These will receive brief mention at this point, in order that the mineralogical description may be reasonably complete, at least for the ore minerals.

Amalgam. The presence of mercury in the Cobalt ores was first reported by Miller [22] in his classic report on this district but the mineral occurrence was later identified by Clevenger,[23] who carried out careful metallurgical tests on ore from the Nipissing mine and proved that the mercury was associated chiefly with dyscrasite and to a lesser extent with native silver, in the form of amalgam.

Native Bismuth. This mineral is occasionally found in very small quantities in all parts of the district, associated chiefly with calcite gangue.

Cosalite was identified by Walker [24] in specimens from the old

[22] *Op. cit.* p. 13.

[23] Clevenger, G. H., ECON. GEOL., vol. 10, No. 8, pp. 770–3, 1915.

[24] Walker, T. L., Univ. of Toronto Studies, Geol. Series, No. 12, pp. 9–10, 1921.

deserted Columbus Mine where it occurs in " radiating masses in smaltite and cobaltite."

Dyscrasite was first recorded by Miller [25] from an analysis by Burrows. It occurred in a specimen from the La Rose Mine. He found it to have the formula Ag_6Sb. Later Walker [26] examined specimens from the Timiskaming and Kerr Lake Mines and found them to consist of a mixture of dyscrasite and native silver in fine intergrowth. He concluded that the so-called dyscrasite was in reality " a eutectic intergrowth of silver and an antimonide of silver, probably Ag_3Sb."

Graphite is mentioned by Miller [27] as occurring " closely associated with the ores of the Cobalt Hill vein, on the Nipissing property."

Matildite was first recorded by Miller [28] who analyzed material from the Nipissing Mine. He obtained an excess of bismuth over the theoretical percentage which was accounted for by associated native bismuth. Ellsworth [29] examined specimens from the O'Brien Mine and found an intimate intergrowth of galena and matildite. Later more material from the O'Brien Mine was examined by the Department of Mineralogy, University of Toronto,[30] and two types of intergrowth between these two minerals were noted, one similar to the grating and one to the island and sea structures.

Millerite is described by Miller [31] as occurring in fine hair-like crystals. The exact locality is not mentioned.

Polybasite was first recorded by Ellsworth,[32] who measured crystals of this mineral and also carried out an analysis on pure material which gave the definite mineral composition $(AgCu)_9SbS_6$. The crystals were of tabular habit and were intimately associated with argentite.

[25] *Op. cit.*, p. 24.
[26] Walker, T. L., Univ. of Toronto Studies, Geol. Series, No. 12, pp. 20–22, 1921.
[27] *Op. cit.*, p. 15.
[28] *Op. cit.*, p. 28.
[29] Ellsworth, H. V., Ont. Bur. of Mines, vol. 25, Pt. 1, pp. 20–21, 1915.
[30] Univ. of Toronto Studies, Geol. Series, No. 12, pp. 70–71, 1921.
[31] *Op. cit.*, p. 20.
[32] *Op. cit.*, pp. 37–39.

Proustite is mentioned briefly in the report by Miller,[33] who does not, however, give either the exact locality or a description of any one occurrence. In 1915 Parsons [34] measured crystals of this mineral from the O'Brien Mine, determining their crystallographic constants and carrying out chemical analysis to confirm their identity with this mineral. In 1922 the same writer [35] describes twin crystals of this mineral from the Penn-Canadian Mine.

Pyrargyrite is recorded by Miller [36] as occurring at the La Rose Mine. He appends a brief description of the crystals, their habit and associations, by Professor Nicol of Queens University.

Stephanite was first reported by Miller [37] who gives a description by Professor Nicol of Queens University and illustrations of the habit of the crystals by R. Schröder of Heidelberg. The crystals occurred in veins of calcite which included also some native silver.

Stromeyerite was first recorded from the Foster Mine by Johnston [38] but the identity of the mineral was often questioned. It was positively identified by Walker [39] in 1927 in specimens from the same mine and was found to be associated with small quantities of bornite and covellite.

Timiskamite is mentioned in the list of Cobalt minerals given by Walker and Parsons [40] but without the exact locality. Its occurrence is recorded in the findings of this paper in a specimen from the Coniagas Mine as mentioned on a previous page.

Ullmannite is recorded from the O'Brien Mine by Johnston [41] but no details of its occurrence are given.

[33] *Op. cit.*, p. 24.

[34] Parsons, A. L., *Min. Mag.* vol. 17, pp. 309–313, 1915.

[35] Parsons, A. L., Univ. of Toronto Studies, Geol. Series, No. 14, pp. 89–90, 1922.

[36] *Op. cit.*, p. 25.

[37] *Op. cit.*, pp. 25–26.

[38] Johnston, R. A. A., Geol. Surv. Can., Summ. Rep., p. 98, 1907.

[39] Walker, T. L., Univ. of Toronto Studies, Geol. Series, No. 24, pp. 18–20.

[40] Walker, T. L., Parsons, A. L., Univ. of Toronto Studies, Geol. Series, No. 20, pp. 59–62.

[41] Johnston, R. A. A., Geol. Surv. Can. Mem. 74, p. 230, 1915.

Xanthoconite is mentioned by Parsons [42] in specimens from the La Rose Mine where it occurs in "approximately hemispherical radiated aggregates of a buffy-brown color, and a few isolated crystals." Another specimen, which was examined by the writer, is recorded under L 2 in an earlier part of this paper.

Before leaving this phase of the subject, it may be well to point out that two minerals, not heretofore recorded as far as the writer is aware, have been added to the list of minerals occurring in this locality. These are safflorite and marcasite. It is rather striking that the former, which is so prevalent in the district, should have escaped mention up to this time. It was assumed formerly that the hard white minerals with metallic lustre, associated with native silver, were, for the most part, smaltite and chloanthite, although the occasional occurrence of cobaltite, arsenopyrite, rammelsbergite, and loellingite, was noted. How far this was from the actual truth, as indicated by the methods now available and used in this investigation, is made clear by the position of smaltite and chloanthite in Table III. Safflorite, on the other hand, is one of the very common minerals in this district, ranking next to cobaltite in abundance. Marcasite was first identified in polished section in the suite of specimens from the Mining Corporation workings but afterwards was found to make up the major portion of M–11 from the same mine. The latter specimen was also examined in polished section but the identity of marcasite as the main mineral in the specimen, which was about 9 x 6 x 3 cm., could be established beyond question without microscopic evidence.

Ore Genesis.

The age relationships of the main minerals found in these ores are fairly clear in general but somewhat obscure in certain particulars.

In his report on this district, Miller [43] gives the following order of deposition as obtained by Campbell and Knight from micro-

[42] Parsons, A. L., Univ. of Toronto Studies, Geol. Series, No. 17, pp. 11–12, 1924.

[43] *Op. cit.*, p. 12.

scopic examination, " 1. smaltite, 2. niccolite, 3. period of movement and fracturing, 4. calcite, 5. argentite, 6, native silver, 7. native bismuth, 8. period of decomposition, 9. erythrite and annabergite." At that time only smaltite, chloanthite and niccolite of the arsenic minerals were recognized as occurring in any great quantity, so that no place is assigned to such minerals as arsenopyrite and cobaltite, although they are recorded as rare mineralogical features of the district. In this part, then, of the present discussion it will be necessary to include, so far as possible, all of the eighteen commoner minerals of the district listed in Table III. Ellsworth [44] includes more of these minerals but groups the mineral products according to their chemical compositions as follows:

I. Arsenides and Sulpharsenides
- 1. Diarsenides: $NiAs_2$, $CoAs_2$
- 2. Monoarsenides: NiAs, NiSb
- 3. Sulpharsenides: CoAsS, FeAsS

II. Calcite, followed by fracturing.

III. Native silver and argentite, native bismuth, sulphides and sulphosalts.

IV. Decomposition Products—arsenates of cobalt, nickel, iron, copper and calcium.

The writer would agree with the general conclusions of Ellsworth but, since the orthorhombic arsenic minerals are found to play a more important role than the corresponding cubic ones, more emphasis will necessarily be laid on them and less on such minerals as smaltite, chloanthite and gersdorffite. In addition the sulphides of iron, copper, lead, and zinc, which are being found in greater quantity now than was formerly the case and which were omitted from Ellsworth's list, will be given what is considered their rightful place in the chronological order.

Adopting the same method of classification, the writer would place the compounds in the following order:

[44] *Op. cit.*, pp. 45–46.

I. Arsenides and Sulpharsenides
- 1. Diarsenides, triarsenides and sulpharsenides of cobalt and nickel
  - (*a*) cubic—smaltite, chloanthite, skutterudite.
  - (*b*) cubic—cobaltite, gersdorffite.
  - (*c*) orthorhombic—safflorite, rammelsbergite, loellingite.
- 2. Sulpharsenides and sulphides of iron
  - arsenopyrite,
  - pyrite.
- 3. Monoarsenides and monoantimonides
  - NiAs—niccolite,
  - NiSb—breithauptite.

II. Calcite, followed by fracturing.

III. Native silver, dyscrasite, argentite, native bismuth, bismuthinite, cosalite, and later calcite.

IV. Sulphides of lead, zinc, copper (galena, matildite, sphalerite, and chalcopyrite), also pyrrhotite, marcasite, tetrahedrite and quartz.

V. Sulpho-salts such as pyrargyrite, proustite, stephanite and later silver.

VI. Decomposition products—arsenates of cobalt, nickel, iron, copper, and calcium, and carbonates of copper.

Discussing the general divisions of this chronological statement in order, the age relationships within the first main division seem to be roughly as indicated with the orthorhombic diarsenides, safflorite, rammelsbergite, and loellingite, slightly later in time of deposition than the cubic minerals smaltite, chloanthite, skutterudite, cobaltite, and gersdorffite. Evidence is forthcoming in sections from the Silver Bar Mine that these orthorhombic minerals have actually replaced the composite crystals of skutterudite, smaltite, and chloanthite. The relations between the skutterudite, smaltite, and chloanthite on the one hand and cobaltite and gersdorffite on the other are somewhat more obscure but it seems probable that they were deposited within a small time interval with varying chemical and other conditions governing the deposition of alternating bands of different material. Whether the rosettes of orthorhombic arsenides, so characteristic of these minerals, are contemporaneous with the cubic arsenides and sul-

pharsenides is more open to question. Arsenopyrite is in the main of slightly later origin than the minerals of the first subdivision of Part I. This is shown by its occurrence in large crystal aggregates either bordering the masses of arsenic minerals of the first sub-division or cutting across them in rough vein-like forms. The position of pyrite is more uncertain but, since it appears to occur in much the same relationships as arsenopyrite, it is grouped with that mineral. The marcasite had clearly been deposited before the deposition of the later silver. This is demonstrated by section 0–16, where this iron mineral is cut by veinlets of native silver. Niccolite and breithauptite are undoubtedly of a later period of deposition, as they replace cobaltite, safflorite, skutterudite, and other minerals of the first two subdivisions in many of the sections.

Not all of the calcite was deposited at one period. The major portion of this carbonate material was undoubtedly introduced between the times of deposition of the arsenic minerals and that of the native silver. There has, however, been a later deposition of this carbonate contemporaneous or nearly contemporaneous with the deposition of the silver.

Much of the so-called native silver of this district is in reality a eutectic mixture of a silver antimonide, dyscrasite, and native silver. Native bismuth, bismuthinite, and cosalite appear to be of the same period of deposition as the silver. The exact position of argentite is somewhat doubtful. From the evidence available it seems probable that most of it has replaced the silver and is consequently to be assigned to a slightly later stage.

Galena, sphalerite, chalcopyrite, pyrrhotite, tetrahedrite, marcasite, and quartz marked the next period of deposition.

Inclusions of silver in sphalerite, probably the first of this division to be deposited, point to a distinctly later time of deposition for the minerals of this division. The order in which these sulphides were deposited would seem to be sphalerite, pyrrhotite, tetrahedrite, chalcopyrite, marcasite, galena, matildite, and quartz. Undoubtedly chalcopyrite is younger than the first three and galena is the youngest of the commoner minerals of the group.

Chalcopyrite has been replaced by bornite, chalcocite, or covellite in a few sections, while galena occasionally shows rims of matildite at the grain boundaries.

The sulpho-salts are of rare occurrence and may represent the last stages of hypogene action. The stage giving rise to decomposition products needs no comment.

The writer has assumed that the diabase sill, or rather the parent magma of this rock, has been responsible for the metallic mineral deposition in these ores. This has been the theory advanced by Miller, Knight, Ellsworth, and others to account for the presence of these ores, and the writer sees no valid argument against it. Knight, in particular, in his extensive report on this district,[45] emphasizes the importance of this igneous intrusion in relation to metallic deposition. He says in part, "In a broad, general way it may be said that the dominating factor in the deposition of the ore-shoots is the Nipissing diabase sill. Wherever silver ore occurs, there also will be found the Nipissing diabase. No silver ore-shoots occur in the entire camp where the diabase sill is absent." Any observations that the writer, with his much more limited opportunities, was able to make, tended to confirm this. Assuming then the basic importance of this formation, the development of the vein minerals in this district may be summarized briefly as follows:

1. Deposition of the arsenic minerals, along with one sulphide and one antimonide.
2. Deposition of most of the carbonate gangue.
3. Period of fracturing.
4. Deposition of native silver and related silver and bismuth minerals and some later carbonate.
5. Deposition of sulphides of lead, iron, zinc, and copper, and of tetrahedrite, accompanied by a quartz gangue.
6. Last stages of hypogene replacement resulting in development of occasional crystals of pyrargyrite, proustite, stephanite, as well as a later silver.

[45] Knight, C. W., Ont. Dept. of Mines, vol. 31, Pt. 2, p. 8, 1922.

7. Period of decomposition and alteration, forming arsenates of cobalt, nickel, iron, copper, and calcium, and carbonates of copper.

In conclusion the writer wishes to acknowledge gratefully the assistance rendered by Professor L. C. Graton of Harvard University, under whose supervision this paper was prepared, and the many helpful suggestions offered from time to time by his colleagues at the University of Toronto. Photographs of diagrams were prepared by the Department of Photography, University of Toronto. Finally grateful acknowledgment is made to the managements of the Mining Corporation, Nipissing, and O'Brien Mines for their courtesy and assistance in the matter of collecting specimens and petrographic data.

Summary.

The more important features of this paper may be briefly stated as follows:

1. Eight new microchemical reagents have been developed for the differentiation of the nine hard white arsenic minerals which are so common in this district and are so intimately associated with each other.

2. The crystal habits, modes of occurrence, and interrelationships of each of these minerals are discussed, as well as their associations with the native silver.

The relative abundance of the common minerals is given, placing smaltite and chloanthite amongst the rarer minerals of the group, and cobaltite at the top of the list.

4. The relations between the quantitative proportions of the other common minerals of this district and their proximity to the diabase sill is worked out and compared to a similar relation for native silver.

5. From a consideration of the above-mentioned relations it would appear that larger quantities of associated arsenopyrite, cobaltite, loellingite, rammelsbergite, or skutterudite have been favorable to the deposition of native silver while niccolite, tetrahedrite, and safflorite in larger quantities are inimical to it.

6. The occurrence of rarer minerals is recorded as observed by other investigators.

7. Details of Ore Genesis, as outlined by previous observers, are amplified to include the occurrence of such minerals as safflorite, and marcasite, which are new for the district, and to fit the commoner occurrence of other minerals which were heretofore considered rare.

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EDITORIAL

RECENT DIAMOND PROSPECTING IN SOUTH AFRICA.

THE remarkable progress in mining generally during late years has been attended by even greater changes in the methods of prospecting. Gone is the old fossicker, to whose optimism and persistence is due the discovery of so many of the world's great mineral deposits, but instead every method—geological, physical or other—, that can be pressed into the service of mankind, is now being employed. There is little doubt that an ever-increasing proportion of the important discoveries of the future will be effected through the adoption of more strictly scientific means.

It may therefore be instructive, as well as of purely general interest, to give a short account of some recent work done in South Africa towards the locating of diamondiferous deposits, and to point out in what way systematically directed investigation has led to the finding of certain astonishingly rich concentrations of that precious gem.

It was primarily the exploitation of the extensive gravel deposits of the south-western Transvaal that caused attention to be redirected to the Atlantic sea-board—not the portion included in South-West Africa containing the long-established Lüderitz Diamond Fields, but to that section immediately to the south of the Orange River, comprised within the district of Namaqualand, Cape Province. It is true that long previous thereto attention had been paid to this very area, but all expeditions venturing therein had failed to obtain practical confirmation for the persistent rumors of the existence of the precious stone in this arid, sparsely populated, and little known region.

In 1925, however, a few diamonds were recovered by W. Carstens from gravels flooring a depression traversing the dunes just

south of Port Nolloth. The next year some more were obtained by R. Kennedy from gravels capping some cliffs not very far to the north of that harbor. These momentous discoveries led to a close investigation by Doctor H. Merensky, assisted by Doctor E. Reuning, of the arid region situated at the mouth of the Orange, on its southern bank, and a thorough testing of the very scanty exposures of pebble-beds, which culminated in the finding early in 1927 of the marvellous terraces of Alexander Bay, of which an excellent account is in print.[1]

Recognizing that the gem was contained in raised beaches, those geologists were able to apply the established principles of shoreline development and were materially aided in tracing the fragmentary and much concealed beach deposits by the presence in certain of them of the fossil *Ostraea prismatica.* Remnants of at least eight terraces have since been identified, standing at levels of from 4 to 40 meters, the highest of which contained the oyster *in situ,* while four of them were productive, though only in sections. The wave-cut and often channeled platform, the nick cut in the bed-rock (schist) at the limit of spring tides, the occasional large wave-worn blocks set in shingle, the storm-beach, and the occasional transverse gullies eroded in the latter and refilled with secondary gravels; all these and a host of other features characteristic of modern beaches were laid bare in all their details for study by the geologist or geographer. More spectacular, however, were the glittering gems that were so frequently disclosed by a few minutes of work with the pick in the loose gravels.

While the richness within certain portions of the deposit was almost incredible, the distribution of the mineral was correspondingly irregular; frequently the productive width hardly exceeded a few meters, the rest of the gravel being either low-grade or barren, while at one spot the whole of the phenomenally rich contents became transferred from one shingle to the adjacent younger one. From two trenches totalling about 900 meters in length and only 6 meters in width, made in the two main terraces that stand at between 27 and 30 meters, there were extracted

[1] P. A. Wagner and H. Merensky, "The Diamond Deposits on the Coast of Little Namaqualand," *Trans. Geol. Soc. So. Africa,* xxxi, pp. 1–41, 1929.

well over one million carats of stones of an average quality quite unprecedented, with a value equal to the bulk of the world's annual consumption of diamonds! All this territory is Crown Land, and, after the recognised claim-areas had been worked out by the discoverers, the Union Government stepped in and has proceeded to develop the field as a State Diggings.

These astounding finds led naturally to a campaign by the Consolidated Diamonds Ltd. on the northern bank of the Orange River, a forbidding stretch of country, not only more complex geologically, but extensively concealed by sand. Indeed for considerable distances the prevailing phyllites are but rarely exposed, the land rising from the sea in a variable slope defined by waves of grayish drift-sands fixed by shrublets. Among the lower terraces, some of which are of fluvial, some of marine origin, several diamondiferous shingles have been found that stand at levels of from 7 to 18 meters, resting in the south-east on deltaic sands and in the north-west on a marine bench cut in phyllites. The paucity of outcrops of the pebble-beds has been skilfully overcome by Doctors W. Beetz and G. Knetsch through the employment of large-scale contoured maps and the fixing of the sites for the prospecting trenches at their proper elevations after making allowances for the depth of the sand and the computed slope of the wave-cut bench.

These shingles are of outstanding geological interest in that they display more clearly even than those at Alexander Bay the successive strand-lines developed by the ocean along an intermittently rising shore. Each shingle slopes gently seawards, and is usually followed by a thin terrestrial sand containing land shells, which is in turn overlapped by the next younger and lower shingle, and so on. The concentration of the diamond is usually greatest along the foot of the ascending storm-beach at the inner side of the terrace. The pot-holing and channelling of the bed-rock is sometimes particularly fine, and such natural "traps" are usually rich. The tracing of the several productive shingles is still in progress, but such work has already shown that they occupy a belt about one kilometer wide and at least 40 kilometers

long. Their exact correlation will be effected by the palæontological examination of their included marine mollusca.

This prospecting work, which has so successfully disclosed a highly important field, constitutes a triumph of scientifically directed operations carried out in an inhospitable, waterless region, and bids fair to prove the persistence of diamondiferous deposits over much of the lengthy stretch between the Orange River and the long-known gem-bearing terrestrial sands of the Bogenfels-Lüderitz diamond fields, which are still producing. The new discoveries will, moreover, cause the latter area to be studied anew and from a fresh angle, which may not improbably lead to fresh economic developments in the northern area.

Between Port Nolloth and Capetown, fragments of raised beaches standing at various levels have long been known to occur, and certain of these have already been proved to be diamond-bearing, for instance those at Klein See, situated at the mouth of the Buffels River, a farm that has been most systematically tested and should very shortly be operating a large recovery plant. The highest terrace here exceeds 35 meters above sea-level.

The origin of these coastal diamonds constitutes a very pretty problem, and one upon which opinion is rather divided. There is no doubt whatever that the waves have over a lengthy period worked over vast quantities of detritus derived from the continent and thereby brought about the concentration of the gem up to within the economic limit. It is furthermore admitted that the Orange River has discharged much waste from its basin, a large area within which are situated not only all the inland alluvial diamond fields, but a host of contributory kimberlite pipes and fissures. Nevertheless, when one takes into account the highly important fact that diamonds are known along the Atlantic coast over a stretch of 900 kilometers at least, there is good reason to doubt the supposition that the Orange was the sole, or even the most important contributor, though the part played by it was undoubtedly considerable.

Working on the hypothesis of multiple origins, Doctor Reuning has been endeavoring to discover a supplementary source

within Namaqualand, and with some measure of success. He paid special attention to the Buffels River, at the mouth of which lie the rich terraces of Klein See. The headwaters of that river tap the western edge of the Bushmanland plateau, a 1000-meter peneplain of probably Late Cretaceous age; a region furthermore known to be pierced by plugs of melilite-basalt and nepheline-melilite-basalt. Now the close relationship of those intrusions to the kimberlites has been maintained by several geologists, including the writer, and, basing his campaign of prospecting on that presumed connection, Reuning has succeeded not only in locating pipes of undoubted kimberlite in that area, but in recovering a few diamonds from gravels along the upper tributaries of the Buffels. Kimberlites situated in the coastal region may well have contributed, while, as the writer has also pointed out, pre-kimberlite sources, too, are not excluded.

Space does not permit of enlarging on this fascinating subject, though sufficient will have been said to indicate the high importance in all further researches of a thorough knowledge of the Tertiary history of the Atlantic littoral; such to include the climatic changes, the varying rate of erosion of the continental mass and the movements of the land relatively to the sea during that epoch. On all such vital points our information is regrettably meager.

The practical results already achieved constitute, nevertheless, the most cogent argument that could be adduced for the closer geological investigation of this portion of South Africa, and give us full confidence that such scientific study, apparently of mere academic interest, would ultimately lead to discoveries of great economic value.

ALEX. L. DU TOIT.

DISCUSSION AND COMMUNICATIONS

PSEUDO-EUTECTIC TEXTURES.

Sir: In reference to Dr. Lindgren's recent paper on "Pseudo-eutectic textures occurring in ore minerals," we have recently observed such textures which may be worthy of discussion.

Covellite is an important constituent of some of the textures observed and a review of the literature furnishes no other examples of covellite in pseudo-eutectic textures. Bateman[1] in a recent paper on covellite-chalcocite does not refer to graphic textures and Dr. Lindgren does not include covellite in his list. It may therefore be concluded that covellite as a constituent of graphic intergrowths is more or less unique.

The specimen of ore containing the covellite intergrowths was collected by Robert D. Longyear and G. M. Schwartz from the dump of a tunnel on the M. and J. Claim, Bulldog Creek, Mount Sopris, Colorado. Mount Sopris is an isolated mountain of intrusive quartz monzonite or granodiorite about 20 miles west of Aspen.

The tunnel penetrates conglomerate, arkose, sandstone and siliceous limestone of the Weber (?) formation where it is upturned by the intrusive. The mineralization is along a series of dip slip faults which contain considerable black gouge. The dip of both faults and beds varies considerably but is commonly about 45° to the southeast.

The hand specimen of typical mineralized rock consists of coarse gray granular quartz with stringers and disseminated sulphide and with malachite stains.

A thin section of the mineralized rocks shows mainly quartz as extremely irregular grains. This does not seem to be vein

[1] Bateman, A. M., "Some Covellite-Chalcocite Relationships," ECON. GEOL., vol. 24, pp. 424–439, 1929.

quartz, but is probably recrystallized sandstone, as indicated by the field occurrence. A few plates of muscovite occur with the quartz and several areas of malachite, calcite and limonite. The only area of sulphide has a rim of malachite.

The polished surfaces show the sulphides in stringers and small areas in the matrix of the quartz grains, which they evidently replaced. The following sulphides were identified: galena, covellite, bornite, stromeyerite, argentite, chalcopyrite, tetrahedrite and sphalerite. Cerussite was also recognized on polished surface, and its identity checked by examination of the powder in oil.

Galena is the most abundant sulphide and often occurs as pure areas, or partly replaced around the periphery by covellite or cerussite. The most interesting feature of the specimens is the beautiful graphic (pseudo-eutectic) intergrowths of galena with stromeyerite, argentite, covellite and bornite. Similar intergrowths of covellite and cerussite also occur. Determination of the minerals involved in these textures was difficult but by use of chemical tests, polarized light, and light etching, the identifications were finally confirmed. The presence of stromeyerite and argentite was further verified by an assay of fragments of the hand specimen which gave 210.45 ounces of silver per ton.

The most common intergrowths consisted of galena, stromeyerite (usually plus argentite) and covellite. It seems that the original intergrowth consisted of galena and stromeyerite-argentite but covellite has replaced the stromeyerite to varying degrees. The greater part of the silver mineral corresponds to stromeyerite, but light etching shows the presence of varying amounts of argentite in places. This association has been described by Guild[2] and is a result of an excess of Ag_2S over the amount necessary to form stromeyerite ($Ag_2S \cdot Cu_2S$). In the galena-stromeyerite intergrowth (Fig. 1) the galena occurs as disconnected elongated forms in a groundmass of stromeyerite. At places the stromeyerite forms a narrow border around the intergrowth. These relations suggest that stromeyerite replaced

[2] Guild, F. N., "A Microscopic Study of the Silver Ores and Their Associated Minerals," ECON. GEOL., vol. 12, pp. 297–353, 1917.

galena and this is verified by Fig. 3, in which an area of galena has been largely replaced by stromeyerite with preservation of the galena cleavage. This pseudomorphism is unusual and furnishes what appears to be conclusive proof that the pseudo-eutectic texture of galena and stromeyerite is a result of replacement.

In most of the intergrowths the groundmass is made up of stromeyerite and argentite with blades of covellite. Fractures and contacts often have a border of covellite with its peculiar tufted form. In places covellite completely replaces the stromeyerite as in Fig. 2. Galena areas are commonly fringed by a rim of covellite without graphic texture in the manner often described for supergene replacement. It seems evident that the covellite is supergene.

The intergrowths of bornite and galena are not as well developed as those described above and are somewhat coarser. The evidence for their formation is not very clear but in them the galena also occurs as isolated elongate forms in bornite so that replacement may be the explanation. If so, they are probably hypogene.

Some of the bornite appears somewhat light colored at ordinary magnifications. Under oil immersion this is found to be due to the presence of chalcopyrite in the bornite as narrow rims around bornite areas and penetrating bornite along the cleavage. The relationships suggest that chalcopyrite has replaced bornite.

At several places graphic intergrowths of covellite in gangue were observed. The transparent mineral seems to be cerussite and usually occurs with an obvious relation to residual galena patches. These are interpreted as a result of oxidation of galena-covellite intergrowths with the retention of some of the covellite.

In connection with the galena-stromeyerite-argentite textures it is noteworthy that a somewhat similar example has been described from Altai.[3]

If additional proof were needed after Dr. Lindgren's paper that graphic intergrowths may form by replacement it surely is available in the specimen described.

[3] Grigoriev, G., "Structures of Mineral Intergrowths in Ores," *Memoirs de la Societe Russe de Mineralogie*, vol. 57, pp. 11–61, 1928. Figure 14.

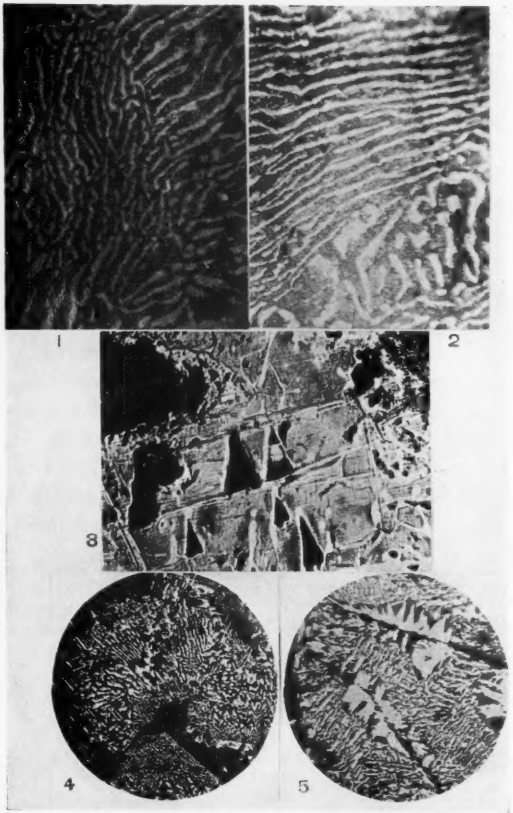

FIG. 1. Graphic intergrowth of galena (white) in argentite (dark). Mt. Sopris, Colorado. × 550.

FIG. 2. Graphic intergrowth of galena (white) in covellite (dark). Covellite apparently replaced stromeyerite and argentite. Mt. Sopris, Colorado. × 550.

FIG. 3. Stromeyerite (gray) has largely replaced galena (white) but has preserved the cubic cleavage of the galena. Stromeyerite was darkened by exposure to arc light during the photographing. Mt. Sopris, Colorado. × 180.

FIG. 4. Graphic intergrowth of magnetite (dark) and hematite. Hema- (Etched hot HCl) Poplar Lake, Minnesota. × 85.

FIG. 5. Graphic intergrowth of ilmenite (white) and hornblende (gray). Anorthositic gabbro (unetched). Duluth, Minnesota. × 85.

The order of formation of the ore minerals seems to be as follows: *Hypogene:* (1) sphalerite, (2) galena and tetrahedrite, (3) bornite. *Supergene:* (1) stromeyerite and argentite, (2) covellite, (3) cerussite. The classification of stromeyerite and argentite as supergene is frankly open to question. Chalcopyrite is later than bornite, but its exact place was not determined. This occurrence also serves to emphasize the complex history of some of these textures. Imagine the difficulty of correctly interpreting the graphic texture of the covellite-cerussite intergrowth if that were the only one observed in the specimen.

With reference to Dr. Lindgren's statement regarding the lack of pseudo-eutectic textures among the hard ore minerals, we have observed certain examples some of which involve ore minerals, but not sulphides, the main group considered by Dr. Lindgren. In studying polished surfaces of the titaniferous magnetites of the Duluth gabbro, graphic textures were noted from time to time. Figs. 4 and 5 illustrate typical examples of hard minerals forming the textures. The following mineral combinations were noted in these textures: magnetite-hematite, ilmenite-plagioclase, ilmenite-augite, ilmenite-biotite, ilmenite-hornblende, ilmenite-chlorite, and other alteration products.

Fig. 4 illustrates the magnetite-hematite intergrowth. From the manner in which this intergrowth is localized around silicate contacts or other boundaries it was concluded that the hematite is secondary and resulted from oxidation of the magnetite. Usually this results in a lattice texture but for some unknown reason it locally resulted in a pseudo-eutectic texture.

In Fig. 5 one example of the ilmenite-silicate series is illustrated. In a single thin section graphic intergrowths were observed of ilmenite with plagioclase, with augite, and with biotite. These are clearly primary and represent contemporaneous formation in so far as can be determined. The hornblende of the intergrowth of Fig. 4 is probably deuteric and represents original augite. In some cases chlorite and sericite have replaced the original silicate. The analogy between these and the galena-argentite-covellite example described above is obvious.

In conclusion it is considered that pseudo-eutectic textures develop by replacement, even supergene replacement, as has been previously stated by one of the writers.[4] They may also develop by more or less contemporaneous crystallization as in the example of ilmenite and silicates. This could scarcely represent true eutectic deposition since ilmenite could not form an eutectic with several minerals in the same rock. It is possible for the texture to develop in hard minerals but it is relatively uncommon and has not been observed except in gabbro and titaniferous magnetites.

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SUPERGENE CASSITERITE IN TIN VEINS.

Sir: I have read with great interest Mr. J. T. Singewald's paper on "Supergene Cassiterite in Tin Veins" in vol. 24 of ECONOMIC GEOLOGY and the subsequent discussion between him and Mr. F. R. Koeberlin in vol. 25. As I have no firsthand knowledge of Bolivian tin deposits I am not in a position to discuss them with any useful effect, but I would like to comment on one point in Mr. Singewald's paper (Mr. Koeberlin's original paper is not available at the moment). On p. 357 of vol. 24 Mr. Singewald says: "Koeberlin cites a personal communication from E. H. Davison that bones dug up at the bottom of some alluvial gravels had the bony tissue partly replaced by cassiterite." Mr. Davison was, I believe, referring to the stags' horns, well known in Cornish literature, that were found in the alluvium of a Cornish stream and described by Mr. J. H. Collins as being impregnated with tin dioxide. It fell to my lot when I was on the staff of the Geological Survey of Great Britain to examine one of these horns that was exhibited in the mineral collection of the British Museum of Natural History as being impregnated with tin dioxide. A microscopic preparation was made for me and a chemical analysis

[4] Schwartz, G. M., *Trans. A. I. M. E.*, vol. 70, pp. 962–963, 1924.

was made by Dr. G. T. Prior. He found no tin but proved that the dark color of the horn was due to the presence of iron oxide. In the microscopic preparation I found no cassiterite or anything suggesting tin, but there were grains of quartz in the cavities of the bone, evidently washed in by water. That I believe to be the explanation of the tin found by Mr. Collins. Small grains of cassiterite had been washed into the cavities of the bone and there was no evidence of tin having been deposited from solution. Mr. Koeberlin refers to these bones on p. 96 of vol. 25. On p. 95 he says that the negative evidence on the solubility of cassiterite has to do with the purer cassiterite from Saxony and the Straits. The tin produced in the Straits is of course noted for its purity but it is common to find cassiterite carrying sufficient iron in chemical combination to be lifted with the magnetic minerals, ilmenite, monazite, and tourmaline, by an electromagnet. The negative evidence of Malaya on the alleged solubility of cassiterite is, I think, particularly valuable because of the high temperature and large amount of the ground-water, which present favorable conditions for an attack on mineral deposits. Neither in Cornwall, where I worked in 1902 and 1903, nor in Malaya, where I have worked since September, 1903, have I found any evidence for the solution of cassiterite by ground-water, nor have I seen any specimen of wood or needle-tin that cannot be regarded as hypogene cassiterite or oxidized stannite.

J. B. SCRIVENOR.

BATU GAJAH,
FEDERATED MALAY STATES.

REVIEWS

Non-Metallic Mineral Products (Except Building Stones). By W. S. BAYLEY. Pp. 529, figs. 126. Henry Holt & Co., New York, 1930. Price, $4.00.

The purpose of this book, as stated by the author, is to furnish a basis for a single semester course on the origin and occurrences of the more important non-metallic mineral substances, and to familiarize the student with the principal sources of information. It serves this purpose admirably but, in addition, does more. It gives in brief form authoritative discussions of various non-metallic substances which are resumés of our present knowledge. It is thus a handy and valuable reference book for everyone. Its use should reach far beyond the class room.

The book deals with classification of non-metallic substances and with occurrence, origin, processes of formation, distribution, uses, production, and statistics of the individual substances. The following chapter headings indicate the contents: Classification; Underground Water; Petroleum and Natural Gas (99 pp.); Solid and Semi-solid Bitumens; Oil Shales; Coal (50 pp.); Salines (77 pp.); Gypsum and Anhydrite; Gems; Abrasives; Sand and Gravel; Ceramic Materials; Monazite and Thorium Minerals; Lithium Minerals; Calcite and Limestone; Lime; Cements; Magnesite and Dolomite; Graphite; Mica, Fluorite and Cryolite; Barite and Witherite; Celestite and Strontianite; Asbestos; Talc and Soapstone; Fertilizers; Phosphates; Sulphur; Pyrite; Pigments and Fillers.

The above list is in no sense merely a catalogue of non-metallic substances. The treatment of each is comprehensive but concise, and the allotted space is proportioned to their importance and interest.

The chapter on classification (20 pp.) is noteworthy. The one on petroleum is really a modern, up-to-date, concise text in itself, and the chapters on coal, salines, and ceramic materials are particularly valuable. Numerous footnotes direct the student to carefully chosen references to carry him further into the subjects. Excellent illustrations add to the attractiveness of a well printed book.

Throughout the book one is impressed by the assiduity and carefulness of the author in choosing his material, his wide knowledge of the literature, and his intimate personal contact with many of the occurrences discussed. The book is a tribute to the author and to the publisher, and

should receive well deserved recognition in the class room. It should be a part of every geological library and will prove a valuable reference for students and producers of non-metallic substances.

ALAN BATEMAN.

Petrographic Methods and Calculations. By A. HOLMES. Second impression. Pp. xix + 515. Thos. Murby & Co., London, 1930. Price, 15 s.

This is a reprint of the valuable book reviewed in these pages about ten years ago (ECON. GEOL. vol. 17, p. 306). It differs very little from the earlier book, except in the addition of a few references to important recent publications. In the last few years so many new methods have been proposed for preparing material for petrographic study that it might naturally be expected that some notice of these methods would have been incorporated into the new text. One looks in vain, however, for any mention of the descriptions by Ross (ECON. GEOL., vol. 21, pp. 454–468, 652, 649; vol. 22, p. 14), Short (*idem.*, vol. 21, pp. 648–664), Schwartz (*idem.* vol, 22, p. 193) and Weymouth (*idem,* vol. 23, pp. 323–330) of new technique suggested for making good sections of firm rocks and of friable materials, and of improvements in the methods of preparing polished sections of opaque minerals. In spite of this lack, however, the volume still remains the best treatise in English that we have on the subjects with which it deals. The reduction in its price is a welcome surprise to those who may need to purchase it.

W. S. BAYLEY.

Asia: An Economic and Regional Geography. By L. DUDLEY STAMP. Pp. 616, figs. 324. E. P. Dutton & Co., New York, 1930. Price, $8.00.

An authoritative book crammed with valuable and interesting firsthand information about this great continent. The author presents the physical features and focuses on the peoples themselves. Part I (seven chapters) deals with the following subjects: The Orthography of Asia; the Structure; the Climates; the Vegetation: the Population; European Explorations; and Asia's Position in the World. Part II treats especially of the individual countries.

The volume is valuable both for the student and the lay reader, and no one interested in Asia should be without it.

Environmental Basis of Social Geography. By C. C. HUNTINGTON AND F. A. CARLSON. Pp. 499, figs. 138. Prentice-Hall, Inc., New York. 1929. Price, $4.00.

This book presents to the student the modern viewpoint that geography is concerned with the relations between man and his environment. It

develops the thesis that this relationship is reciprocal, *i.e.*, environment influences man and man modifies his environment and both are subject to continual change. The following chapter headings give an idea of the contents: Nature and Classification of Geography; Man's Distribution and Activities; Man's Environment; Location; Maps and their Interpretation; Major Climatic Regions of the Earth; The Seasons as Geographical Influences; Weather and Man; Lands and their Utilization; Utilization of Forest, Agricultural, and Urban Land; Minerals and Industries; Water and its Utilization; Biological Environmental Elements; Social Factors; Geography of Civilization.

It is a well presented book, teeming with information, and one that should be in every library.

ALAN BATEMAN.

Petrography of the Pioche District, Lincoln County, Nevada. By JOSEPH L. GILLSON. U. S. Geol. Survey Prof. Paper No. 158D, 1929.

This "contribution to general geology" is one of a series of short papers that the Survey has now been issuing for seventeen years. It describes two phases of a cupola of a batholith in Nevada, intruding some formations from the Cambrian to the Miocene(?) It seems likely that the late residual magma produced considerable changes in the early crystals that grew in the magma. These changes are so striking as to indicate that the residual magma or some other magmatic product of this Pioche intrusive moved farther, or moved in greater volume, or had effects more in contrast with that of the early magma, than is commonly the case. Dr. Gillson credits Dr. Fenner with this idea, and concludes that emanations from the magma not only produced contact metamorphism in the Miocene(?) lavas, but also made a difference in the magma itself and in the igneous rocks formed from it at several stages of its evolution. He calls special attention to the attack of the residual magma on the early solidified border phase of the same magma. If such an attack is to be classed as an igneous rather than a metamorphic process (as the reviewer is willing to agree), it may be included with processes of igneous differentiation, or at least as a feature modifying differentiation. All credit should be given to Dr. Gillson for calling attention to the matter, and it may be worthy of further elaboration than this incidental statement in the summary of a ten-page paper. It seems to be a process that should be distinguished from the gaseous transfer in a liquid magma described by Dr. Fenner.

The comments that follow are, therefore, in no sense to be taken as discounting the merit of the description of an occurrence where such processes seem to furnish a satisfactory explanation. The reviewer is

not sure that Dr. Gillson has proved his case,—what sort of field or laboratory evidences could prove that gas acted on a solid, rather than a liquid acting on a semi-solid mass? Nevertheless, as a presentation of Dr. Gillson's conclusions rather than a statement of fact, the process seems to be a good explanation for the Pioche occurrence.

The changes that occur in the early phases of the intrusive bring up a difficulty in terminology. We are accustomed to speak of the result of reaction between a crystal and a residual magma from which it had not been much separated as a deuteric effect; but in this case a large body of rock is supposed to have become solid—though probably still very hot—and then been attacked by the still fluid parts of the intrusive from some distance away. Possibly the process is comparable with that producing luxullianite or greisen, with which petrographers have long been familiar but about the origin of which there has been some disagreement. Should such rocks be classed as (1) igneous rocks, (2) contact metamorphic rocks, (3) endomorphosed rocks, (4) metamorphic rocks, (5) igneous rocks with deuteric alteration, (6) pneumatolytic rocks, (7) hydrothermal rocks, or (8) autometamorphic rocks? Dr. Gillson uses several of these terms for the Pioche occurrence,—uses them separately and in combinations that leave the reader in some doubt as to whether all refer to one process, or to several distinguishable processes.

A discussion of terminology or criticism of words comes dangerously near to quibbling. The reviewer believes it should be attempted in this case, however, because the ideas presented refer to magmatic differentiation, a process which is of major interest to petrographers, and about which there should be as little ambiguity of statement as possible. In the paper in hand there are passages that required a very careful reading and a study of the context before the outline given above could be formulated. Before criticizing particular features of the paper, the reviewer hastens to plead guilty, himself, of having written carelessly at times. Criticism seems to be needed in this case because loose statements appear to be more numerous than in Dr. Gillson's earlier papers or in other "contributions" of the Survey series.

On page 80 there is a statement that "the only way in which potash could have been introduced into the magma, as it was" also "in the solid rock after consolidation, was by means of volatile emanations." These words are not an exceptional accidental mis-statement but are repeated at several places in the paper. On careful study it appears that when Dr. Gillson says "introduction into the magma" he means moving from one place to another in the magma. It can not be that he has confused the magma and an early phase of rock (as he does elsewhere in the paper, pp. 83, 84 and 86), for he includes both magma and rock in the quotation given. "Introduction into the magma" is clearly an error. Things may

have been introduced into the stock or into the cupola, or into one part of the magma; but they were no more introduced into the magma than fat is introduced into milk when the cream rises to the top of a milk bottle.

Again, the "volatile emanations" which are credited with doing the work of differentiation probably never left the magma and are not properly called emanations according to any dictionary or geologic usage known to the reviewer. There are several better terms in use for such constituents,—mineralizers, easily volatile constituents, fugitive constituents, or even dissolved(?) gases.

Taken at their face value these statements in the report clearly give the impression that a new explanation is being proposed for differentiation, viz., by introduction; but they sound new only because they are inaccurately stated.

The reviewer would add a plea, not directed at Dr. Gillson more than at others, but none the less apropos, to use the term deuteric within the limits originally given it by Dr. Sederholm. "I think that it would be advisable to discriminate between such metasomatic changes which belong to a later period of metamorphism, *i.e.* are secondary in the strictest sense of the word, and those which have taken place in direct continuation of the consolidation of the magma of the rock itself. I propose to call the latter deuteric, as distinct from secondary changes." Effects of gases or residual magmas outside the intrusive are clearly secondary in the rocks affected, and not covered by his term deuteric. For reaction effects inside the igneous rock before it cooled, "deuteric" serves well when there is no sign that the reacting materials have moved far into any solid rock. For the effects of a late residue on an early solidified border phase such as here noted by Dr. Gillson, perhaps a new term is needed.

Dr. Gillson furthermore makes a number of assumptions that certain controversial matters are settled. The most striking of these is the assumption of gas emanations in and around an intrusive. The work of Dr. Morey of the Geophysical Laboratory, and of Dr. Niggli of Zurich, who formerly worked with Dr. Morey, has been very enlightening as to the relations of gases to magmas. Yet these two experts who apply their physical chemistry to geologic problems, *disagree* as to whether a residual pegmatitic emanation is above or below its critical temperature. Like Dr. Fenner, they are very cautious in their references to gas. They speak of the "streaming" of dissolved gases, and of gas bubbles rising and escaping from a magma. Most petrographers with less knowledge of physical chemistry are also cautious. Dr. Gillson writes as if the gaseous state of magmatic emanations were all settled. For example, he says (p. 83), "the gases passing upward from below . . . were rich in potash." If this was dissolved gas it would be better to describe it as a potash-bearing rest-magma rich in dissolved gases.

Again, there is the statement that "the potash feldspar . . . continued to grow after consolidation" (p. 80), which sounds as if a considerable mass of the rock was solid, whereas the evidence cited shows only that certain mineral grains were solid.

Several such assumptions need a more detailed statement of evidence before they are acceptable: "the magma stoped its way upward" (p. 83); "the replacement of quartz by orthoclase" (pp. 81 and 82); "the wide distribution of minute euhedral grains of augite . . . so nearly unique that it would probably not be found in different rock types" (p. 80); "this replacement was not a magmatic corrosion" (p. 82); and even the age of the "Miocene(?) lavas" (p. 77).

FRANK F. GROUT.

Geochemie in ausgewählten Kapiteln. By W. J. VERNADSKY. Authorized translation from the Russian by E. KORDES. Pp. xii + 370. Akademische Verlagsgesellschaft M.B.H. Leipzig, 1930. Price, $6.25.

The first edition of Vernadsky's work was printed in French in 1924. A revised edition was published in Russian. This German edition is translated from the Russian edition, but contains many additional items, not contained in the original.

The book differs from most of those dealing with geochemistry in that it discusses the effect of chemical changes in the Earth's crust brought about by organic as well as by inorganic substances. The first chapter gives a brief history of geochemical thought. The second treats of the chemical substances in the crust; the third of the geochemistry of manganese; the fourth of silica and the silicates; the fifth of carbon and organic substances, and the sixth of radioactive elements and their compounds. The literature is combed for information on all these phases of the subject and the conclusions reached by the various authors are abstracted and generalizations are built upon their conclusions. An annotated bibliography of 834 articles concludes the volume. The work appears to be very thorough. It contains many tables, and emphasizes the fact that the development of the earth is the result of processes due to the activities of organic as well as of inorganic bodies.

W. S. BAYLEY.

The Earth for Sam. The Story of Mountains, Rivers, Dinosaurs and Men. By W. MAXWELL REED. Illustrated. Harcourt, Brace & Co., New York. Pp. 390.

This is a readable account of the history of the Earth and of its life, written for a boy of grammar school age. The story of the development of animals and plants is told in a way that should interest any normal boy

of 14 or 15 years of age. It is illustrated by many good pictures, not a few of which will attract the attention of the youngster by their comical flavor. The book is a good one to present to a young friend who is scientifically inclined, because while it is written in a racy style, it is at the same time accurate in its teaching.

BOOKS RECEIVED

Mineral Resources of the United States, 1927; Part I, Metals, pp. 782; Part II, Non-Metals, pp. 687. U. S. Bur. of Mines, Washington, 1930.

Petroleum Development and Technology, 1930. Petroleum Division, Amer. Inst. M. and M. Eng., New York, 1930.

Oil and Gas in Oklahoma. Okla. Geol. Surv. Bull. 40; Vol. II, pp. 501, pl. 11, figs. 70, maps (folder) 41; index. Vol. III, pp. 663, pl. 2, figs. 136, maps (folder) 50, index. Norman, Okla., 1930 (July). Detailed discussions by many authors of geology, occurrence and possibilities of oil and gas, taken up by counties; an encyclopedia of information.

Reports of the Norwegian Svalbard Expeditions, 1906–1926, edit. by ADOLF HOEL. (2) Mollusca of Tertiary of Spitsbergen, by J. P. J. RAVN; (3) Burning Coal Seam at Mt. Pyramide, by W. WERENSKIOLD AND I. OFTEDAL; (4) Reindeer, by A. WOLLEBAEK; (5) Lichens, by B. LYNGE; (6) Coal Deposits and Coal Mining, by A. HOEL; (7) Biology of Spitsbergen Char, by K. DAHL; (8) Geology of Northwestern Spitsbergen, by O. HOLTEDAHL; (9) Lichens, Bear Island, by B. LYNGE; (10) Hope Island, by T. IVERSEN et al.; (11) Mollusks, Red Bay and Grey Hook (in German), by W. QUENSTEDT.

No. 15. Geology of Bear Island, Norway, by G. HORN AND A. K. ORVIN, pp. 152, figs. 70, pl. 9. Geography, stratigraphy, structure, geologic history (in English).

No. 17. Coals of Svalbard, by G. HORN, pp. 60, figs. 5, pl. 5 (in German). Jacob Dybwad, Oslo, 1928.

Monographs, Geol. Surv. of Brazil: A Lower Llandovery Graptolite Zone on Rio Trombetas, Para, by C. J. MAURY, pp. 40, figs. 3. Fossiliferous Limestone at Bom Jesus da Lapa, Bahia, pp. 7. Rio de Janeiro, 1929.

Geology of North Singbhum including Parts of Ranchi and Manbhum Districts. By J. A. DUNN. Pp. 166 + xxvii, figs. 13, pl. 17, map. Memoirs Geol. Surv. of India, vol. LIV, Calcutta, 1929. Stratigraphy, historical and economic geology.

Lehrbuch der allgemeinen Bodenkunde. By A. STEBUTT. Pp. 518, figs. 55. Gebruder Borntraeger, Berlin, 1930. Price, 37.50 M.

The Aluminous Refractory Materials: Kyanite, Sillimanite and Corundum, in Northern India. By J. A. DUNN. Pp. 129 + xxi, pl. 12. Memoirs Geol. Surv. of India, vol. LII, Pt. 2, Calcutta, 1929. Distribution and origin of the deposits.

Structure and Stratigraphy of Wichita Falls Area, Texas. By H. F. SMILEY. Pp. 24, pl. 5, figs. 4. Deep Oil Development Company Publication.

Commercial Possibilities of the Texas-New Mexico Potash Deposits. By J. S. WROTH. Pp. 143, figs. 5. U. S. Bur Mines Bull. 316. Price, 25 cts.

The Devonian of California. By C. R. STAUFFER. Pp. 38, pl. 5. Univ. of Calif. Pub. vol. 19, No. 4, 1930.

Notes on Later Geologic History of Tahiti, Society Islands. By H. WILLIAMS. Pp. 17, figs. 10. Univ. of Calif Pub. vol. 19, no. 5, 1930. Volcanoes, reefs and lagoons, recent movements of shore line.

Mining Industry in Idaho, 1929. By S. CAMPBELL. Thirty-First Annual Report. Pp. 300.

Artificial Abrasives and Manufactured Abrasive Products and their Uses. By V. L. EARDLEY-WILMOT. Pp. 144, figs. 14, pl. 19, tables 11. Abrasives, Pt. IV, Canada Dept. Mines No. 699. Price, 20 cts.

The Flora of the Denver and Associated Formations of Colorado. By F. H. KNOWLTON. Pp. 142, pl. 59. U. S. Geol. Surv. Prof. Paper 155, 1930. Flora and Paleobotany. Price, 80 cts.

Revision of the Lower Eocene Wilcox Flora of the Southeastern States. By E. W. BERRY. Pp. 196, pl. 50, figs. 32. U. S. Geol. Surv. Prof. Paper 156, 1930. Price, 75 cts.

Geology and Coal Resources of the Meeker Quadrangle, Moffat and Rio Blanco Counties, Colorado. By E. T. HANCOCK AND J. B. EBY. Pp. 52, figs. 2, pl. 11. U. S. Geol. Surv. Bull. 812–C, 1930. Price, 30 cts. Stratigraphy, structure, coal.

Geology and Oil Resources along the Southern Border of San Joaquin Valley, California. By H. W. HOOTS. Pp. 96, figs. 3, pl. 17. U. S. Geol. Surv. Bull. 812–D, 1930. Price, 50 cts. Stratigraphy, structure, physiography, petroleum geology.

Mining in the Fortymile District, Alaska. By J. B. MERTIE, JR. Pp. 18, figs. 2. U. S. Geol. Surv. Bull 813–C, 1930. Price, 5 cts. Gold placers in the oldest mining district in interior Alaska.

Geology of the Eagle-Circle District, Alaska. By J. B. MERTIE, JR. Pp. 168, figs. 6, pl. 12. U. S. Geol. Surv. Bull. 816, 1930. Price, 50 cts. Descriptive and economic geology.

The Scientific Fundamentals of Gravity Concentration. By JOSEF FINKEY. Trans. by C. O. Anderson and M. H. Griffitts. Pp. 294. Bull. School of Mines and Metallurgy, Rolla, Mo. Tech. Series No. 1. Price, $1.00. A thorough mathematical discussion of the principles underlying jigging and table concentration. A fundamental research in the fields of the jigging, tabling and classification of ores.

Copies of books mentioned under "Reviews" or under our "New Book List" (see advertisement page) may be purchased through our Journal Bookshop by writing to W. S. Bayley, University of Illinois, Urbana, Ill.

SCIENTIFIC NOTES AND NEWS

Charles Camsell, Deputy Minister of Mines, Canada, is president of the Royal Society of Canada this year, also of the lately organized Canadian Geographical Society.

Chauncey L. Berrien has become assistant general manager of the Anaconda Mining Company.

J. E. Spurr has been spending the summer at Alstead, N. H.

H. Foster Bain has returned to New York after attending the World Power Conference in Berlin.

Donald H. McLaughlin, of Harvard University, returned to Cambridge early in September after a summer of field work in Mexico.

W. L. Cumings, geologist for the Bethlehem Steel Company, is spending three or four months in Chile.

William F. Prouty, professor of economic and structural geology, University of North Carolina, has been conducting a class of students on a transcontinental study tour of the United States, embracing most of the National Parks and a number of mining centers.

Louis A. Wright, of Mayflower Associates, recently returned to London after a visit to the United States.

J. B. Tyrrell received last June from the University of Toronto the honorary degree of LL.D.

H. C. Goodrich, of the Utah Copper Company, has been elected president of the Utah Society of Engineers.

Otakar Matousek, professor of geology at Charles University, Prague, has been visiting the United States.

Charles H. Behre, Jr., has been made associate professor of economic geology at Northwestern University.

Henry Krumb will return to the United States in October after a summer in Europe.

Norman Smith has recently returned home from Flin Flon, Manitoba, where he has been organizing a geological department for Hudson Bay Mining and Smelting Co.

John A. McLaughlin, formerly mine superintendent at Copper Mountain, Canada, is in charge of mining operations in southern Russia for the Soviet Government.

V. Gibbs is chairman of the board of directors of the Sulphide Corporation, Broken Hill, New South Wales.

David White, of the National Research Council, has announced fellowships for 1930 in the Division of Geology and Geography as follows: H. J. Fraser, Cambridge, Mass.; N. Hinchley, St. Louis, Mo.; R. Lupher, Pasadena, Calif.; J. S. Smiser, Princeton, N. J.

V. M. Kreiter, chief geologist of the Central Geological Committee, U. S. S. R., sailed for Europe, July 23, after visiting mining districts in the United States.

W. R. Cox, formerly connected with the field service of the U. S. Land Office, has opened an office as consulting mining engineer at Portland, Ore.

James R. Finlay and Arthur Notman now have offices in the Bank of Manhattan building at 40 Wall Street, New York.

Marcel E. Touwaide, after two and a half years in Borneo, is now prospecting for oil in French Morocco.

Kirby Thomas is engaged in investigation work on the salt deposits of the Carolinas and Virginia.

David B. Reger, of Morgantown, West Virginia, lately resigned his position as associate geologist of the West Virginia Geological Survey.

J. W. Steele, of the U. S. Geological Survey, is doing exploration work for the Sinclair interests in Portuguese West Africa. H. B. Soyster has taken his place as supervisor of the Survey station at Casper, Wyoming.

The Western Society of Engineers, coöperating with the Illinois Geological Survey, has arranged an educational exhibit of the mineral resources of the State, in the Society's rooms in Chicago, starting the middle of August.

The Geological Survey of Canada has had 58 parties in the field this season, with a personnel of 240.

John G. Marzel, Wyoming State Geologist, has sent out notice of the annual field conference of the Association of American State Geologists, to be held in Montana and Wyoming on August 24–29.

The American Institute of Mining and Metallurgical Engineers announces fall meetings for 1930 as follows: Coal Division, at Pittsburgh, Pa., Sept. 11–13; Iron and Steel, Chicago, Ill., Sept. 22–26; Petroleum Division, Tulsa, Okla., Oct. 2–3; General program and Amer. Mining Congress, El Paso, Texas, Oct. 13–16; Petroleum Division, Los Angeles, Calif., Oct. 17.

The Organization Committee for the 1932 International Geological Congress has sent out its first circular, giving names of committee members and tentative outlines of excursions.

The recently published 20-volume index (336 pages) of ECONOMIC GEOLOGY for 1905 to 1925, compiled by J. M. Nickles, may be obtained for $3.00 from W. S. Bayley, University of Illinois, Urbana, Ill.